Edinburgh Napier UNIVERSITY

Evaluation of the performance and user satisfaction with air source heat pump installations in older social housing stock

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Report

in respect of SFHA Energy Ideas Fund

for

Ayrshire Housing

EXECUTIVE SUMMARY

Ayrshire Housing, in collaboration with the Scottish Energy Centre (SEC) at Edinburgh Napier University, have worked over the last 4 years to define the practicality of integrating energy efficient retrofit measures into a portfolio of hard-to-treat housing stock in the village of Dailly. The project sought to define the options for energy efficiency and mitigation measures into existing housing stock in order to work towards improved housing stock quality standards and reduce fuel poverty for vulnerable tenants.

Following this, Ayrshire Housing completed the installation of Air Source Heat Pumps (ASHP) to replace inefficient electric storage heaters in 33 of their 1950's construction dwellings and funding from the SFHA Energy Ideas Fund supported a study by the Scottish Energy Centre in order to provide real-life in-use data of the ASHP systems' performance for a variety of lifestyle groups over a 12 month period.

The main findings from the study were:

- The residents reported that their comfort levels within the internal environment have improved considerably since the installation of the ASHP
- When comparing the reported comfort levels before and after the installation of the ASHP all participating residents reported greater thermal comfort and improved indoor air quality
- The opinion of the residents towards the ASHP was, on-average very positive, and did not change between the interviews conducted 6 months after ASHP was installed and 24 months after install
- 75% of participants reported that they have heard little or no noise coming from ASHP since it was installed
- 75% of residents reported similar or lower utility bills whilst using the ASHP compared to previous years when electric storage heating was used
- All residents participating in the study reported that the response time of the ASHP was much faster than that of the replaced electrical storage heating, meaning the house would begin to feel warmer faster. Furthermore, they reported that the controls for the ASHP were 'much more' intuitive than those of the old heating system.

A key outcome from the research will be the development of better guidance and support mechanisms so that users can get the greatest benefit out of such systems. This will be of wider general application as air source heat pump technology is rolled-out especially in off-gas grid areas for both new build and refurbishment projects, and will hopefully build confidence amongst social landlords in the effectiveness of the technology.

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PREAMBLE

1 Objectives

Ayrshire Housing completed the installation of air-source heat pumps (ASHP) to replace inefficient electric storage heaters in 33no. 1950s houses in Dailly, Ayrshire in 2014. This village was outwith the current gas supply network area and thus affordable and sustainable energy solutions were sought in order to meet improved housing stock quality standards and reduce fuel poverty for vulnerable tenants. The total cost of the installations was £266,000 (ex. VAT) and Ayrshire Housing was successful in obtaining a grant of £132,000 from the UK Department of Energy and Climate Change; through the Renewable Heat Premium Social Landlords Competition.

The proposed study was to build on a pre-installation energy modelling exercise undertaken by the Scottish Energy Centre at Edinburgh Napier University in order to provide real-life in-use data of the systems' usages for a variety of lifestyle groups over a 12 month period. A key outcome of the study was the development of better guidance and support mechanisms so that users can get the best greatest benefit out of such systems. This will be of wider general application as air source heat pump technology is rolled out especially in off-gas-grid areas, for both new-build and refurbishment projects, and will hopefully build confidence amongst social landlords in the effectiveness of the technology.

2 Background

The association has a stock of 33 former Scottish Special Housing Association (SSHA) dwellings in the village of Dailly. All were built in 1955 and are of traditional construction. Originally heated by coal fires they were subsequently installed with electric storage heaters in 2001. EPC energy efficiency ratings (SAP 2005) were in the range 36 to 44, despite the addition of cavity fill, enhance loft insulation, and double glazing over the years.

The sample stock is typical of much of social housing provision in rural areas. It is envisaged therefore that if the effectiveness of implemented retrofit measures can be demonstrated, it would provide assistance to social landlords in planning their modernisation strategies. In terms of business development, it would assist designers, contractors and suppliers to establish niches in the application of established but still fairly novel (for social landlords) technologies.

The initial study undertaken by the Scottish Energy Centre (Currie, 2013) evaluated fabric-first improvement options and identified the costs & benefits of approaches which focus on either simply augmenting the existing heating systems as against more extensive renewal of the heating and ventilation systems. It also identified what additional measures could usefully be introduced to further enhance thermal performance and air quality still further for the benefit of the resident(s).

2.1 Overview of Test Dwellings

A representative sample of the Dailly housing stock into which the ASHP technology had been installed was identified; which included end- and mid-terraced 1.5 and 2-storey dwellings (Fig 1 to 4).

Fig. 1 to 4 Front elevation of participating dwellings on Hadyard Terrace, Dailly, Ayr.

A field survey of these households was undertaken together with key members of Ayrshire Housing staff. This was used to help identify the existing conditions and construction of each dwelling and to identify the installation requirements for data-logging equipment in order to undertake the study. Heating bills (where available), occupancy demographic, and heating type were recorded, with additional information on secondary heating, usage and comfort.

Since their initial construction in the 1950's the buildings have undergone thermal performance upgrades including the fitting of double glazing, new doors, and loft insulation. The replacement of the original electric storage heating installed in 2001 with ASHP's was completed in 2014.

The residents who volunteered to contribute to this project were granted anonymity in accordance with the University's Code of Ethics. Therefore, the four participating Households are referred to as Household 1, 2, 3, and 4 (alternatively D1 to D4). The identities have been shared with Ayrshire Housing with permission from each resident.

2.2 Baseline Energy Consumption

Meter readings were available to calculate 3 years of electricity consumption for Household 1 and 2 years for Household 2 which represents the consumption levels before the installation of the ASHP which took place during the first quarter of 2014. No meter readings were available to calculate baseline (pre-ASHP) electricity consumption for Household 3 and 4.

The meter reading data were collected from utility bills, some of which were marked as 'accurate' and others marked as 'estimated' readings. The annual consumptions were calculated from readings recorded at the start of each year, statistical trend analysis was utilised to extrapolate the meter readings back to the start of January thereby providing the figures to calculate 12 months of electricity consumption.

Table 1 shows the average (mean) annual electricity consumption for Households 1 and 2. The results show the percentage of household electricity consumed for space & water heating and that used for other household electrical equipment i.e. kitchen appliances, lights, entertainment equipment etc.

The results for both Households show that the annual electricity consumption changes very little over the measured years (relatively low SD). On average, 66% of the annual electricity in Household 1 consumption was used for heating, Household 2 had a much larger demand for electricity due to its occupancy profile, with 49% of the average annual electricity demand used for heating.

Table. 1 Baseline Annual Total Electricity Consumption

	Household 1	Household 2
kWh/year (mean)	5,345	15,097
Standard deviation	110	21
kWh/m²/year (mean)	51.8	160
% of which was for heating	66%	49%

The occupancy profile difference between the 2 monitored Households extends to explaining the large difference in annual energy consumption. Household 1 is occupied by a single retired resident who, in past Building User Surveys self-reported to being very energy efficient and frugal with matters of utility bills and described himself as being 'out of the dwelling for the majority of daylight hours'. Household 2 is occupied by 3 adults, 2 of whom described themselves as being at home for the majority of the week.

2.3 Baseline Energy Costs

The metering infrastructure in Household 1 and 2 was configured with 2 utility meters and both dwellings subscribed to the Scottish Power ComfortPlus Control Tariff. This tariff charges electricity consumption at 2 rates, the 1st rate referred to as 'all/day' is applied to electricity consumption by electrical equipment, appliances, lights etc. other than heating, referred to in this report as ‘other’. The 2nd rate referred to as ‘control’ is applied to electricity consumption for space and water heating, referred to in this report as ‘heat’.

Utilising the annual tariff information published by Scottish Power and collected from the residents’ utility bills, the annual electricity bill has been calculated for Household 1 and 2 for the years before the installation of the ASHP where data was available. Fig. 5 and 6 charts the calculated annual electricity costs for heating, the daily standing charge, and the other electrical appliances.

As previously discussed, Household 3 and 4 did not possess historic or current billing information, however, during the interview surveys conducted at the time the residents of Household 3 stated they were paying up to £60 a week on all electricity demand during the winter months, which changed to an estimated £10 a week during the summer months. The residents of Household 4 stated that they paid £35 a week to the electricity meter during the cold months which changed to £5 a week during the warmer months. Not enough specificity within this information means that an annual cost on utility bill cannot be extrapolated with confident accuracy.

For Household 1 and 2 the trend in annual utility bill cost follows that of the annual energy consumption with only slight variation per year. For the tariffs applicable to Household 1 the daily standing charge has dropped considerably over the 3 years (-34%) resulting in that cost making up 26% of the annual bill in 2011 and dropping to 16% of the annual bill in 2013. Both the price (p/kWh) for ‘heat’ tariff and ‘other’ tariff have increased over the charted 3 years, increasing by 12% for ‘other’ traiff and 22% for the ‘heat’ tariff. These changes in tariff costs result in the cost for heating increasing from 37% of the final bill in 2011 to 46% in 2013. In this 3 year period the electricity consumption (kWh/year) for heat in Household 1 increased by 9%, the utility bill for heating increased 33%. The combination of changes in the tariff over the 3 years means that the total annual electricity consumption increased by 6% and the utility bill increased by 8%.

The total calculated utility bill for 2011 was £587, £578 for 2012 and £635 for 2013. The average annual utility bill for Household 1 during those baseline years was £600.53 (SD = 25)

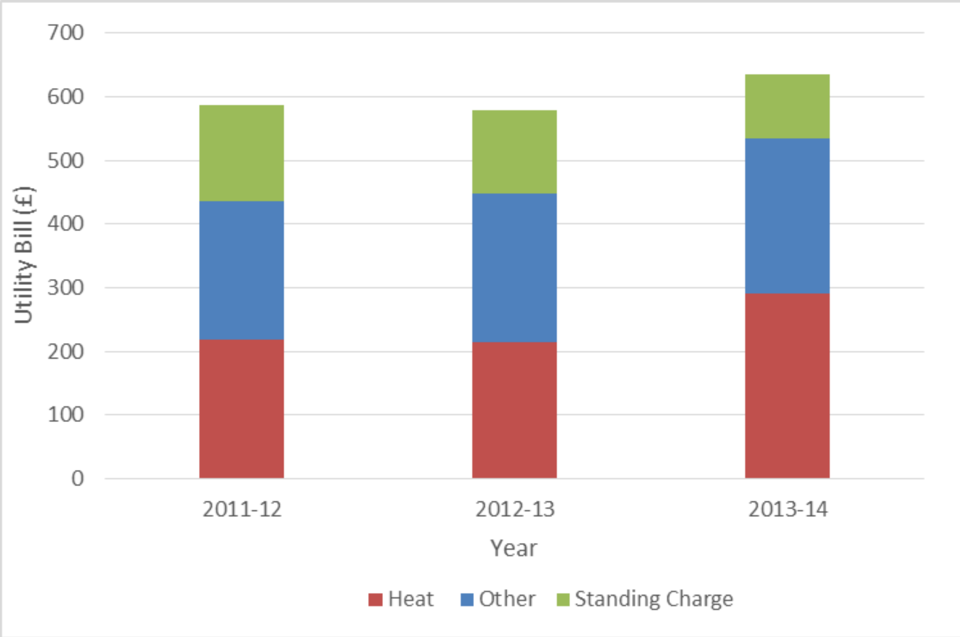

Fig. 5 Baseline annual electricity bill for Household 1 before ASHP

During this time Household 2 was subscribed to the same utility tariff but using a different payment method, therefore a slightly different set of costs are applied to this tariff. Fewer price changes were applied to this tariff during this shorter comparable period so the cost of electricity to Household 2 varies little between the 2 years. The monetary difference between the 2 tariffs for the 2 Households is relatively negligible. The much larger demand for electricity on the non-heat or 'other' and more expensive tariff is part of the explanation for the higher utility bill in this Household. Higher demand for electricity for heat and power proportionally decreases the percentage of the bill related to the standing charge. For both years 61% of the utility bill was for other electrical appliances, 32% for heat and 7% on the standing charge.

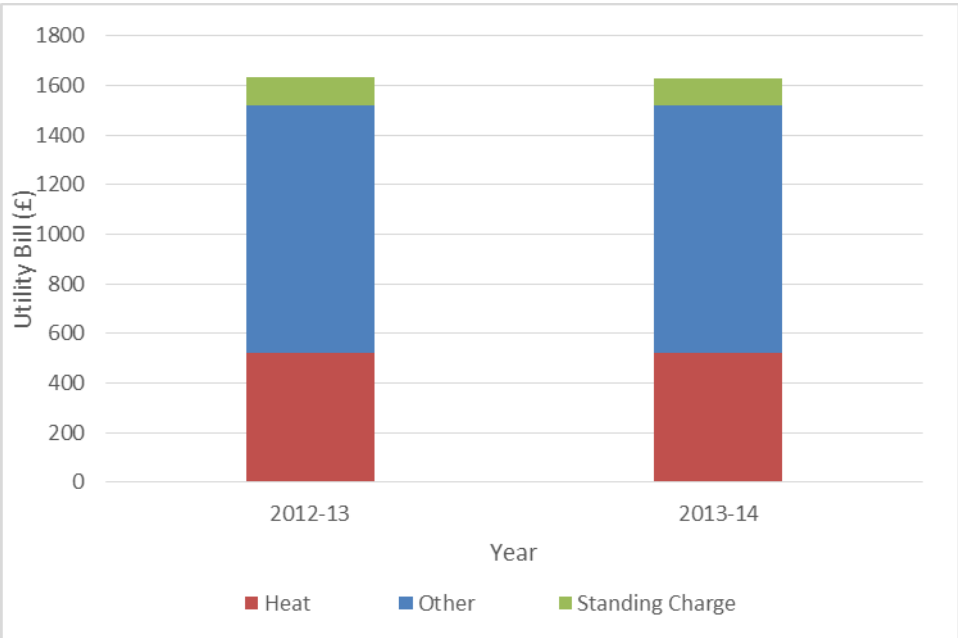

Fig. 6 Baseline annual electricity bill for Household 2 before ASHP

2.4 Air Source Heat Pump

Coolheat Energy Ltd were contracted by Ayrshire Housing to install Daikin Altherma – Low temperature split air source heat pumps in the Dailly properties (Fig 7). Heat pumps utilise the thermodynamic efficiency of a closed cycle working fluid to gain thermal advantage as lower-entropy is required to compress the fluid than is released in the high grade heat generated. In such heat pumps the heat delivered can be 3-4 times the electrical energy consumed, and is often referred to as the Coefficient of Performance (COP).

Fig. 7 Outdoor component of ASHP as installed at the Hadyard Terrace properties

The installed units include an outdoor heat pump unit, an indoor heat pump unit installed adjacent to a domestic hot water tank and a user interface to control the system operation, together with a thermostat. The units are connected to the home electricity distribution system which is subsequently connected to the Scottish Power, most of which appear to operate using the Scottish Power local distribution network on a Comfort Plus Control Tariff. Present tariff structures being offered by utility providers do not allow such renewable technologies to financially benefit the occupiers fully and, unless the ASHP operation can be re-profiled to operate for significant periods at lower unit rates, this will not necessarily be translated into lower cost to the residents.

3 Evaluation of ASHP Energy Performance

Utilising the telemetry ista devices, electricity demand and heat generation data have been collected from the ASHPs installed at Household 1 and Household 2. The data have been collated and analysed monthly for 1 year from the start of February 2015 to the end of January 2016.

Section 3 is divided into 6 subsections, which presents and discusses the total household consumption and energy and cost performance characteristics of the installed ASHP's. Each subsection presents analysed results from either 2 or 4 of the monitored Households where the data was available.

The electricity consumption data for the ASHP is presented as kWh/month, after which the annual electricity demand of the ASHP is compared to the total electricity demand of the Household. The percentage split of electricity end-use is presented and discussed, this is followed by presentation of costs for powering the ASHP per month using the current tariff structures.

The heat consumption data is presented as kWh/month and kWh/year and describes the amount of space heating generated by the ASHP to meet the residents demand. The monitored internal and external temperatures are also presented and used to interpret fluctuations in heat consumption over the 12 month period.

This Section is concluded with the presentation of the coefficient of performance (COP) data, which represents the factor of heat generation divided by electricity consumption.

3.1 Total Household Electricity Consumption

Electricity meter readings were collected during the 5 visits to the 4 participating Households. Table 2 shows that the Household 1 consumed the least amount of electricity over the monitoring period, whereas Household 2 consumed the most within this sample, Household 3 and 4 consumed similar amounts of electricity during that time. The residents' occupancy profile and energy efficiency behaviour scores (EEBS) describe the differences in electricity consumption between the 4 Households that data is presented in Section 5.

The total electricity consumption has been calculated from the meter readings collected between 12th March 2015 and 11th March 2016 (the 2nd year of energy consumption since the ASHP was installed).

Table 2 Post ASHP Installed Annual Total Electricity Consumption

	Household 1	Household 2	Household 3	Household 4
kWh/year	5,193	11,484	8,512	8,085
kWh/m²/year	50.3	121.3	91.7	86.9

The different occupancy profiles and slight differences in building type can explain the differences observed in annual electricity consumption. The occupancy profiles for Household 1 and 2 are discussed in Section 2.2 and the building archetypes are shown in Section 2.1. Household 3 is occupied by a 4 person family, 3 of which describe themselves as being out of the house for the majority of the week, and rated their energy use behaviour as being energy inefficient. Household 4 is occupied by 2 adults in full time employment also rating themselves as energy inefficient.

3.2 ASHP Electricity Consumption

Telemetry energy loggers were installed on the ASHPs in 2 Households. These loggers where installed during January 2015. The data collected from these loggers were used to calculate the monthly and yearly electricity consumption for the ASHPs. The total yearly electricity consumption of the ASHPs is presented in Table 2, and monthly in Fig.8. In this Section, the term year relates to the 12 month period between1st Feb 2015 to 31st Jan 2016.

Table. 2 Annual Total Electricity Consumption of ASHP

	Household 1	Household 2
kWh/year	3,261	5,210
kWh/m²/year	31.6	55.0

As anticipated, the ASHPs consumed more electricity during the colder winter months. Adopting the heating season defined by SAP (Standard Assessment Procedure) i.e. space heating will be demanded only during the months October to May, then the ASHP at Household 1 consumed 92% (2,990 kWh) of its annual electricity demand during that heat season and the ASHP at Household 2 consumed 82% (4,258 kWh) of its annual electricity demand.

Fig. 8 presents the total monthly electricity consumption for the ASHP with the average monthly external temperature overlaid. The charted data shows that when the external temperature is below 10 °C the ASHP is in demand for space heating increases.

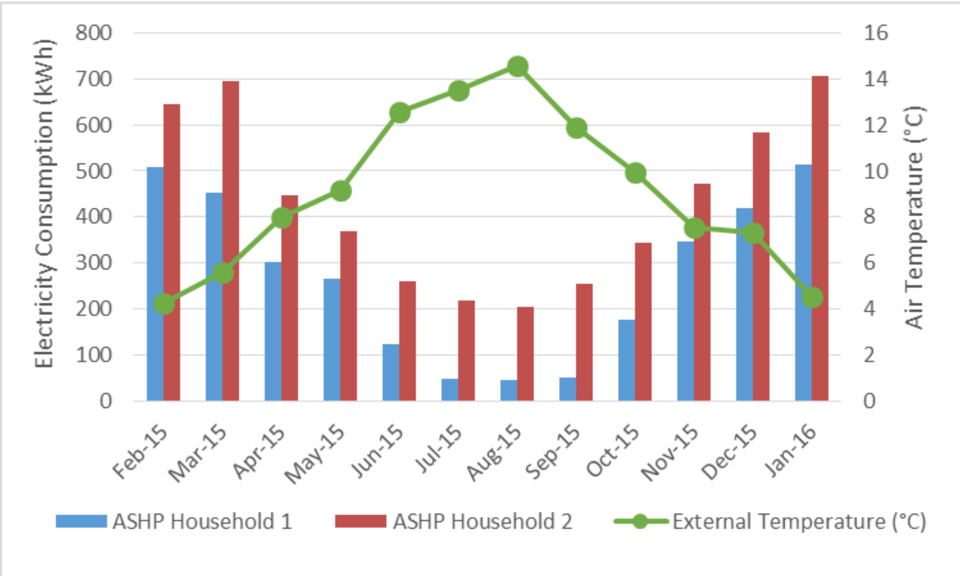

Fig. 8 Monthly total ASHP electricity consumption, and average monthly external air temperature

The differences in electricity consumption by the ASHP relates directly to the amount of heat generated to meet the temperature demand in each home. Section 3.5 presents and discusses the heat power generated by the ASHPs. The lower electricity consumption by the ASHP in Household 1 will relate to the lower and/or shorter requirement for space and water heating described by the occupancy profile.

3.3 ASHP Percentage of Total Electricity Consumption

The electricity consumption collected for the ASHP has been compared to the total Household electricity consumption as calculated from meter readings collected during 2015. The headline figures are presented in Table 3 and Fig. 9.

Meter readings were collected on 5 occassions between 11th January 2015 and 11th March 2016. In this Section the term year refers to the period between 12th March 2015 and 11th March 2016 (365 days or 1 year).

During this period Household 1 consumed 5,193 kWh/year of electricity. The ASHP consumed 3,281 kWh/year of electricity during that period, representing 63% of the total electricity consumption for the Household. This percentage spilt for heating is similar to but lower than the calculated percentage split for space heating calculated from data recorded before the installation of the ASHP (66%) (see Section 2.2)

Over the same period Household 2 consumed 11,484 kWh/year of electricity, the ASHP was responsible for 45% (5,210 kWh/year) of yearly electricity demand. Again, this split is similar to but lower than that calculated for the data recorded before the ASHP was installed (49%) (see Section 2.2).

The subtle differences in percentage split for heating during the storage heating years and ASHP year may be due to differences in external temperature and quantity of hot water required over those respective periods.

Table. 3 Percentage of electricity consumed by ASHP

	Household 1	Household 2
% of total	63%	45%

The meter readings where collected to closely represent heating and cooling seasons (winter and summer months). The heating season consists of 8 calendar months (start of Oct to start of June) and is widely expected as the months when space heating is used and in highest demand which is correlated with the months of dropping and coldest external temperatures. Using this basic definition of when space heating is in demand, enough data was collected to calcuated the percentage of electricity consumption by the ASHP for majority parts of the 2 heating season and all of the summer period which occurred during the monitoring. The ASHP logger at Household 2 was installed later in the 1st heat season and has been omitted from the results in Fig. 9.

The results presented in Fig. 9 show that, as expected, during the heating seasons the ASHP electricity consumption represents the majority (between 70 and 80%) of total household electricity demand. During the months representing the summer period (10th June 2015 to 01st September 2015) the proportion of total electricity used by the ASHP was considerably lower at between 20 and 30% which will almost certainly relates solely to the demand for water heating as further described in Section 3.5.2.

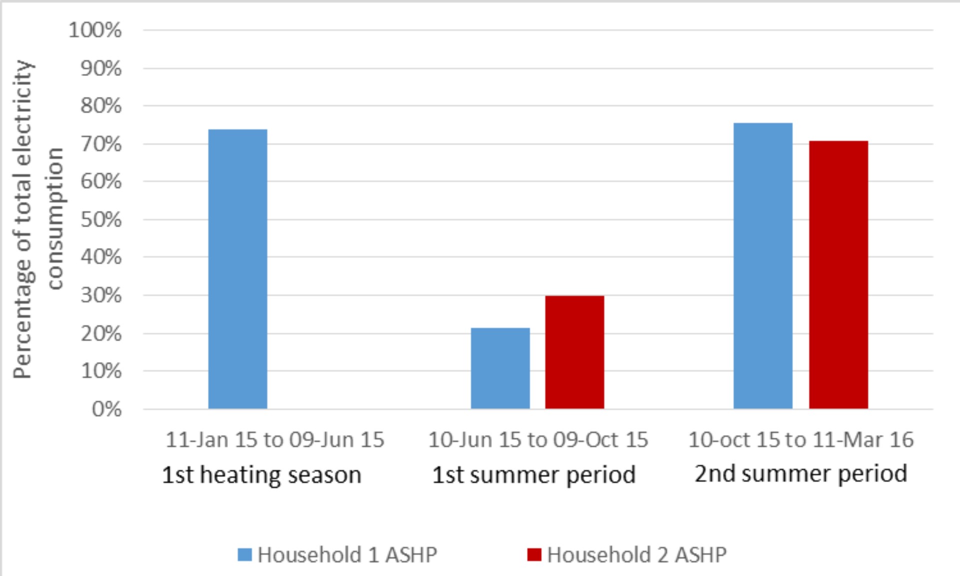

Fig. 9 Percentage of electricity demanded by ASHP per season type

Domestic electricity consumption for appliances and equipment other than for space and water heating is less dependent on temperature, floor area or number of residents, it is more dependent on a complex relationship between the residents' or families' energy use behaviour, daylight hours and proportion of time the residents spent away from the dwelling. Therefore, the amount of electricity consumed on 'other' electrical equipment is proportionally in keeping with that observed in dwellings with similar occupancy profiles in other energy monitoring research projects.

The electricity consumption for the remaining electrical equipment and appliances in the household during this monitored period equals 1,914 kWh/year for Household 1 and 6,275 kWh/year for Household 2. This value is in keeping with the magnitude observed from the pre-ASHP baseline energy data analysis, where electricity consumed for 'other' appliances was on average 1,825 kWh/year (SD = 58) and 7,964 kWh/year (SD=11) respectively.

3.4 ASHP Electricity Cost Performance

The monthly and annual electricity bill has been calculated, presented and discussed for each monitored household. These can be found in Fig 10 and Fig 11, the headline utility cost per year figures are presented in Table 4.

In keeping with the electricity consumption values discussed in Section 3.2, the calculated utility bill and cost to run the ASHP are considerably lower for Household 1 compared to Household 2, this is due to the differences in occupancy profile and recorded internal temperatures discussed in Section 5 and 3.5.

Table. 4 Annual Utility Bill Costs

	Household 1	Household 2
Total £/year	777	1,689
Total £/m²/year	7.5	17.8
ASHP £/year	427	720
ASHP £/m²/year	4.1	7.6

The monthly electricity utility bill has been calculated for Household 1 and 2 with a graphical breakdown presented in Fig. 10 and 11 respectively.

The month consumption for electricity other than ASHP was not logged to the same resolution as that of the ASHP, therefore the calculated annual consumption for electricity on 'other' household equipment, appliances, lighting etc. is divided evenly over the 12 month, although not accurate, experience in this field of research shows that electricity consumption per month varies little over the year.

Meter readings collected during 2015 shows that after the ASHP was installed the meter reading on the 2nd electricity meter for 'control' heating had not changed. Therefore, all electricity, including that used by the ASHP to heat the space and water is being charged that the 'all/day' rate and therefore higher tariff, this is factored into the costs presented here.

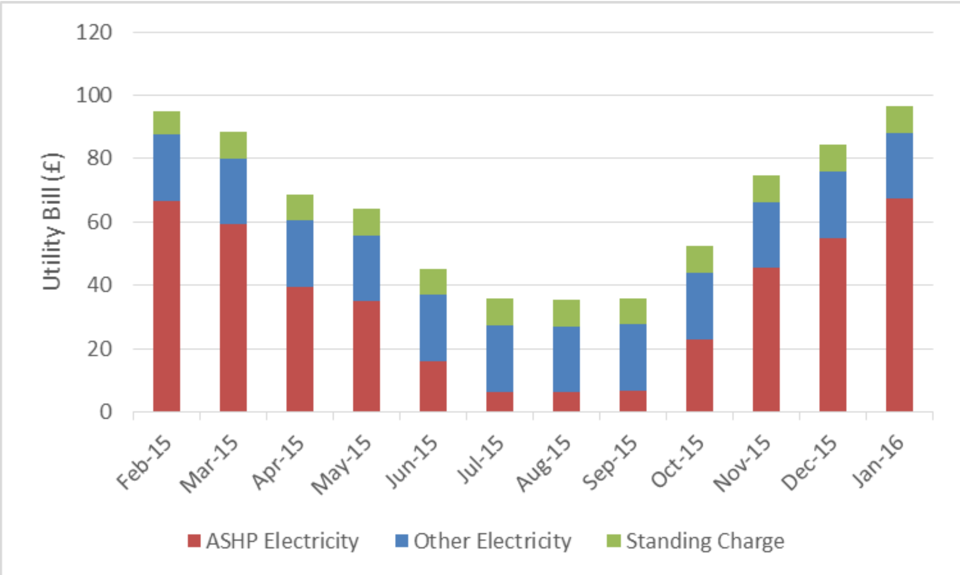

Fig. 10 Calculated total monthly electricity bill for Household 1 after ASHP

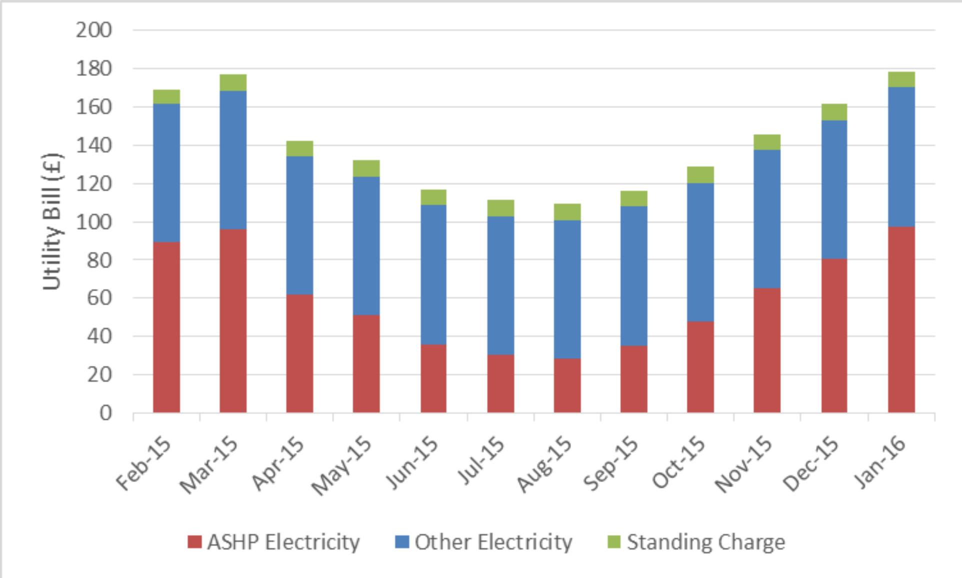

Fig. 11 Calculated total monthly electricity bill for Household 2 after ASHP

Differences between utility bills before and after installation of ASHP are discussed in Section 4.

3.5 ASHP Heat Generation

The heat energy generated by the ASHP installed at Household 1 and 2 was monitored during the same 12 period as that for the electricity consumption (1st Feb 2015 to 31st Jan 2016). The annual heat generation values for both households are presented in Table 5, the monthly values are presented in Fig. 12 and Fig 13.

Table. 5 Annual Total Heat Generation of ASHP

	Household 1	Household 2
kWh/year	6,979	13,497
kWh/m²/year	67.6	142.6

As anticipated, the ASHP generated more heat energy during the colder months (the heating season). The monthly heat generation profiles of the ASHPs follows the same statistical profile of the electricity consumption for both households. The ASHP at Household 1 generated 93% (6,480 kWh) of the annual demanded heat during those 8 months (Oct to May), the ASHP at Household 2 generated 81% (10,988 kWh) of its annual demanded heat during those same 8 months. These are graphically presented in Fig 12 and Fig. 13.

3.5.1 Temperature Differences

The monthly recorded external temperatures at Hadyard Terrace are presented in Fig. 8 (Section 3.2) and show a familiar seasonal temperature profile with the Jan and Feb being the coldest months (4^0C) and July and Aug being the warmest months (14°C). Before and after the installation of the ASHP five months of internal temperatures were recorded at Household 1 and 2 (10 months in total). The monthly average internal temperature from the recorded data shows that the temperature at Household 1 was maintained around 17°C each month, with a relatively low variation in monthly internal temperatures (SD = 1.1). The monthly internal temperature at Household 2 was maintained at 19°C also with a relatively low amount of variation between the monitored monthly average temperatures (SD = 1.2). These temperatures are somewhat lower than the commonly quote 21°C, the temperature loggers in this study were positioned in centralised location in each house which will include temperatures from living, sleeping and corridor zones which are not always heated to 21°C.

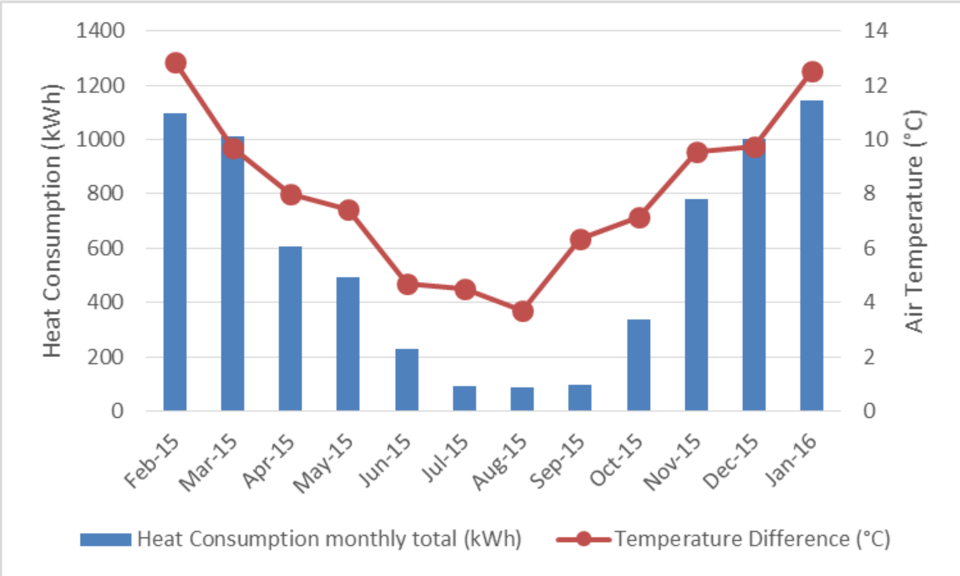

Fig. 12 Calculated total monthly heat generated by ASHP at Household 1 after ASHP

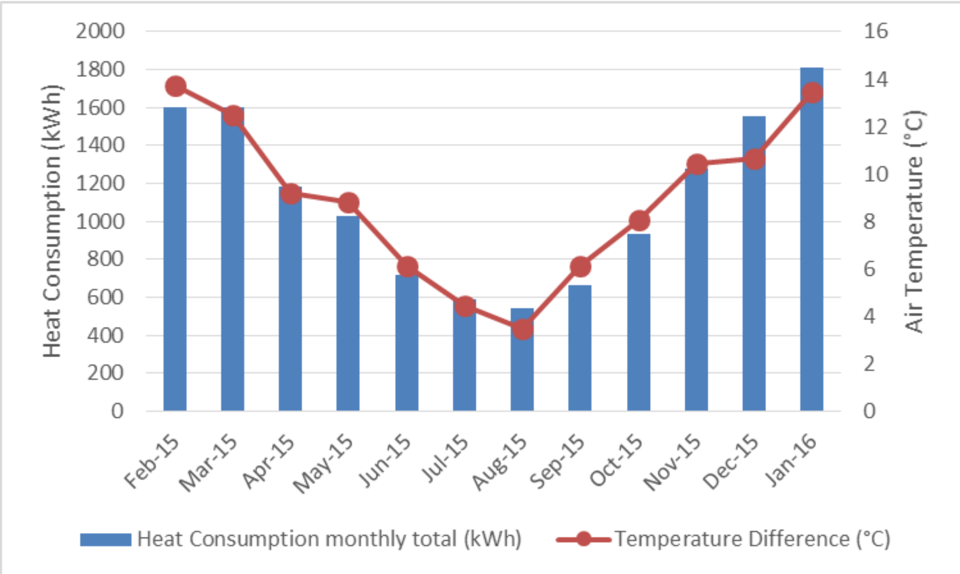

Fig. 13 Calculated total monthly heat generated by ASHP at Household 2 after ASHP

The recorded monthly average temperature for Household 1 (17°C) and Household 2 (19°C) were used respectively to complete the missing monthly values. For the accompanying heat generation analysis the internal minus

external temperature difference was calculated and plotted in Fig. 12 and Fig. 13.
These values demonstrate a strong positive correlation between the heat generated and temperature difference in Household 1 (r=0.95) and Household 2 (r=97). The small variation in these results are due to the extrapolated internal temperatures and the fact that external temperatures have little effect on hot water demand.

3.5.2 Water Heating

The monthly heat generation data presented in Fig. 12 and Fig. 13 shows that the heat generation recorded at the ASHP includes both heat for space and water, therefore the heat generation and electricity consumption of the ASHP during the summer months (June to Sept) may relate solely to water heating.

It could be inferred that the heat generation during the summer months represent that electricity demand for water heating, this is based on the SAP dwelling design criteria that states space heating requirement is reduced to 0 because of increased solar heat gain, increased external temperatures and reduced fabric and ventilation heat losses during those 4 summer months. Therefore, the summer heat generation has been extrapolated and presented to estimate the amount of heat which had been generated by the ASHPs for annual water heating.

In the case of Household 1, the considerably higher (2.5 times) ASHP heat generation in June compared to Jul, Aug and Sept warrants the removal of June's data for the calculation of average monthly water heating. Excluding the month of June, the total heat generation of the ASHP during the 3 months of lowest heat demand is 272 kWh, with an average of 90.7 kWh/month (SD = 3.4). Which, if constant every month will translate to 1088 kWh/year for water heating.

In the case of Household 2, the heat generation for the month of June has been removed, for the reason that if Household 1 demanded space heat in June, it is reasonable to believe that Household 2 did also. Excluding the month of June, the total heat generation of the ASHP during the 3 months of lowest heat demand is 1,794 kWh, with an average of 598 kWh/month (SD = 50.5). Which, if constant each month would translate to 7,176 kWh/year for water heating.

Domestic hot water demand is calculated based on the number of residents, accurately predicting hot water consumption is complex and highly dependent on resident behaviour, however, the consumption rate is not dependent on weather and is therefore often relatively consistent for every month.

If the ASHP telemetry data are showing electricity consumption for space and water heating, it can be inferred that 16% of the annual heat generation at Household 1 is for water heating and 53% of the annual heat generation at Household 2 is for water heating.

Typically, the measured split of energy use on space and water heating is approximately between to 30% - 50% for water heating. Therefore, the assumptions made for Household 2 are supported. The lower than expected hot water demand calculated for Household 1 is likely to be caused by the occupancy profile therein, and potential margin of error in the calculation method.

3.6 ASHP Coefficient Of Performance

In this situation, the COP describes the efficiency of the ASHP by describing the relationship between the amounts of thermal energy (heat) produced (kWh) and the amount of electrical energy consumed (kWh) to produce that heat. The higher the COP the more thermal energy produced (kWh) for every unit of electricity consumed (kWh). The annual COP for the ASHP at the 2 households are very similar at 2.1 and 2.6 kWh/kWh (see Table 6) meaning that the ASHP at each dwelling generated over twice as much heat energy over the year for every kWh of electricity consumed.

Table. 6 Annual Coefficient Of Performance

	Household 1	Household 2
kWh/kWh	2.1	2.6

The monthly COP profile for Household 2 is different from that calculated for Household 1 (see Fig. 14). The efficiency of the ASHP at Household 1 is lower than that calculated for Household 2, with the highest value (2.4) occurring during December and the winter months, then lowest (1.8) during the summer months. The monthly profile for the ASHPs COP at Household 2 is consistently higher per month and shows less monthly fluctuation than the ASHP at the other dwelling. The ASHP COP at Household 2 is highest in May (2.8) and during late winter and late summer, then lowest (2.3) during the colder months (Feb, Jan).

Due to the higher overall heat energy demanded by Household 2 (Section 3.5) the ASHP in that dwelling appeared to operate with more efficiency. Interviews with the residents at each dwelling revealed that the resident in Household 1 preferred using the heating intermittently in an effort to reduce consumption and save money. The residents in Household 2 preferred a warmer environment over energy reduction and commented on keeping the ASHP settings on those pre-set at installation which has the system heating the home and water for long periods with low grade heat.

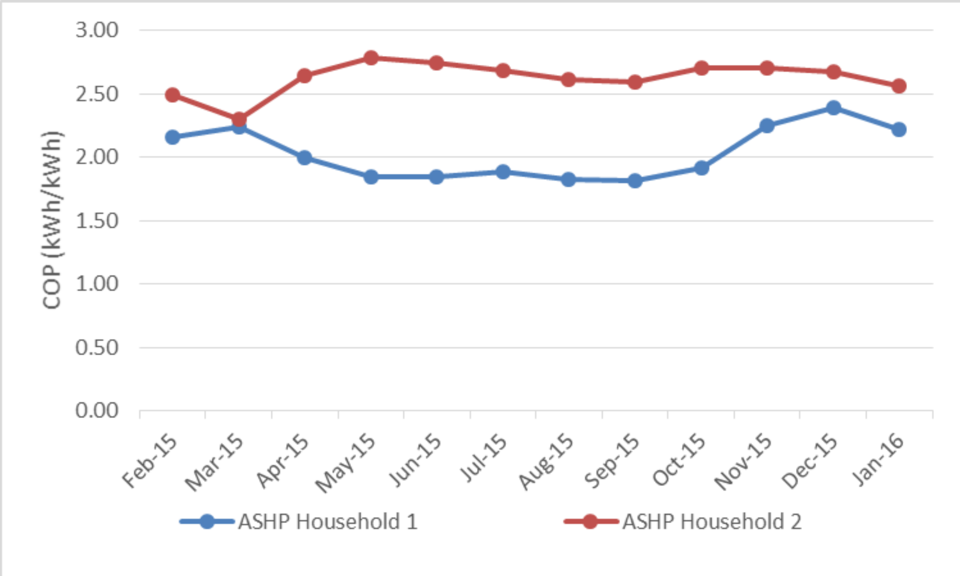

Fig. 14 Calculated monthly COP for ASHP at Household 1 and 2

The monthly COP was tested for statistical variation by finding the proportion of the total variation in the monthly COP that can be attributed to the linear relationship with the external temperature. This is done using the coefficient of determination (r2). The ASHP COP at Household 1 showed a medium strength negative linear association ($r^2 = 0.63$) with the external temperature, the ASHP COP for Household 2 showed a weak positive linear association ($r^2 = 0.25$) with the external temperature. Suggesting that with these two ASHP units the level of COP cannot be completely described by the external temperature.

4 Baseline and ASHP Energy and Cost Comparison

This Section uses the data presented and discussed in Section 2.3 and Section 3.4 for 5 and Household 2 to discuss the differences in annual electricity consumption and utility bill before and after the ASHP installation.

Before and after the ASHPs were installed a resident within each of the 4 participating households were asked the frequency by which they conducted a set of energy saving activities. Although the answers changed slightly between interviews the analysis of the results show that the energy efficiency behaviour scores (EEBS) for each household has not changed significantly ($p>.05$) over that time period.

The annual electricity bill for Household 1 after the installation of the ASHP was calculated to be £777. This bill is higher, arguably considerably higher than the annual electricity bills of the past 3 years. 2015’s bill is £140 higher than that of 2013, and £177 higher than the average cost of the 3 annual bills between 2011 and 2013.

Four cost scenarios have been generated and presented in Fig 15. To evaluate the changes in utility bill over time each scenario uses the first year when baseline data was available as the index year for comparison. Scenario labelled Costs ‘N’a have been calculated using the actual costs as charged on the observed utility bills. Scenarios labelled Costs ‘N’b use the control heating tariff that was being charged to the old storage heating system and ceased to apply after the ASHP was installed. Scenarios labelled Costs 1'a or b' and 2'a or b' are different because of the years tariff applied to that years energy consumption. Costs 1 mean that the bill cost is calculated using the Scottish Power tariff specific to the year in which the energy was consumed, this is cost in real-terms and will include changes in tariff prices. Costs 2 are calculated by applying the Scottish Power Tariff for energy consumed in 2011 to all subsequent years of energy consumption.

Comparing Costs 1 and 2 scenarios show that the utility tariff and rates in those tariffs change little between the years. Comparing Costs a. and b. scenarios show that the considerable increase in utility bill cost at Household 1 in 2015 is the result of the ASHP electricity being charged to the higher 'all/day' tariff as opposed to being on the less expensive 'control' or a comparable 'low cost renewable' tariff.

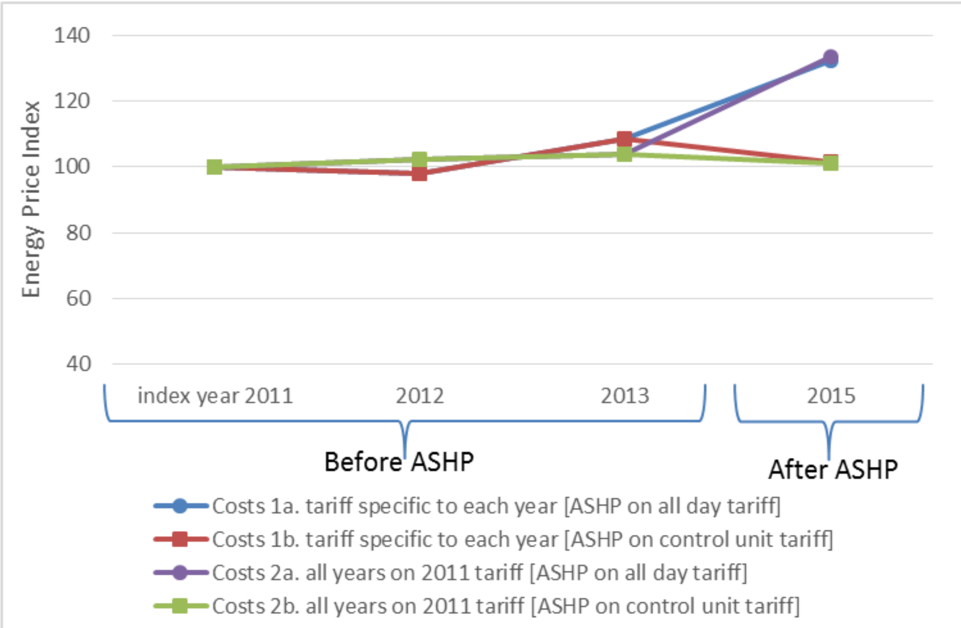

Fig. 15 Annual baseline and post ASHP utiliy bills for Household 1

The results from the same analysis done for Household 2 show that the 2015 utility bill was slightly (£56) higher than the average price of the utility bill in the years before the ASHP was installed. The tariff costs and electricity consumption for the years preceding the ASHP differ marginally. Similar to the results for Household 1, if the total cost of the 2015 utility bill was calculated using the lower 'control' rate for the electricity consumption of the ASHP (Costs 1b and 2b scenarios) then the 2015 utility bill would have been 14% lower than 2012 or 21% lower in real-terms.

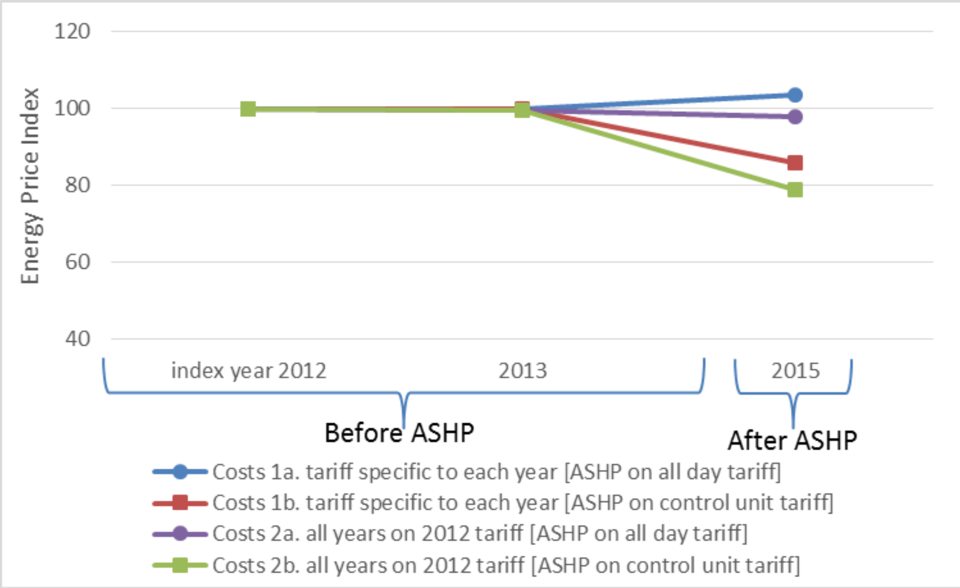

Fig. 15 Annual baseline and post ASHP utiliy bills for Household 2

These utility bill findings were not expected given the increased efficiency of the new heating system, namely COP of >2.0 compared to that of the storage heating (COP of 1). Comparing all the energy data show that the ASHP at both dwellings generated considerably more (99% and 82% respectively) heat during 2015 than was demanded on average during the years when the original (storage) heating was in use, see Fig 16.

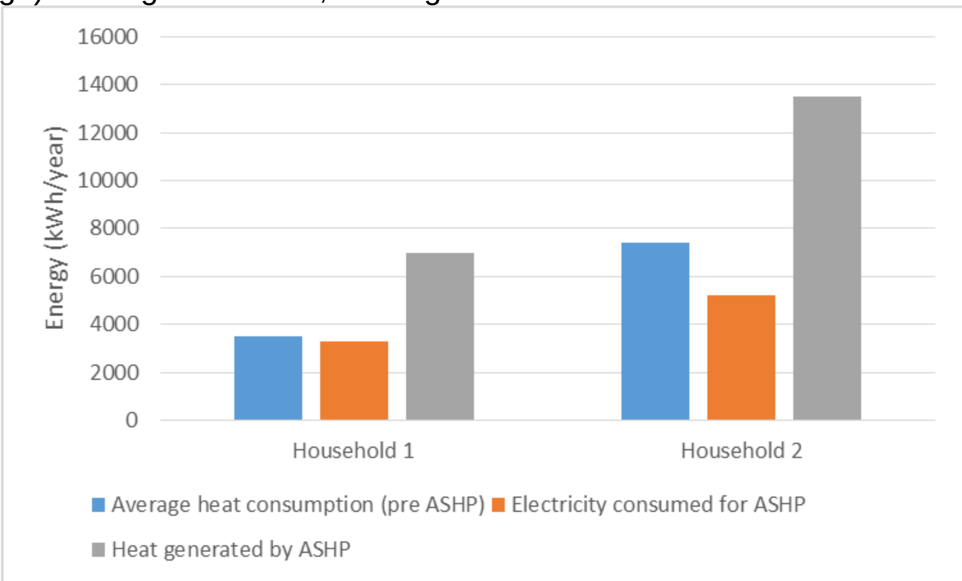

Fig. 16 Comparison of heat consumed before and after installation of ASHP

The other 2 households participating in this study were unable to present current or past utility bills, nor were they in a position to provide recent or past meter readings. However, both sets of residents within each dwelling adamantly reported during the face-to-face interviews that their weekly electricity bill during 2015 had reduced by an estimated 32%. The utility tariff details were captured from the installed pre-payment meter which revealed that, much like Household 2, their electricity tariff had not changed significantly since the monitoring began. Similar to the findings on changes in energy efficiency behaviour score (EEBS) for the residents in Household 1 and 2, the before and after ASHP the EEBSs for these 2 households had not changed significantly (p>.05) over that time period.

Analysis of the local monthly external temperatures for the 4 years between 2011 and 2015 show that the average winter temperature for 2015 was 0.6°C higher than 2013, and 0.6°C lower than the average winter temperature for 2011. Analysis of the variation between the monthly temperatures across those 4 years shows that there was no statistically significant difference ($p>.05$) in external temperature. Therefore, external temperatures are considered very unlikely to be the cause for the increased demand for heat generation.

It is commonly observed, and widely referred to as the rebound-effect (Berkhout et al 2000); which occurs when a new low-carbon/low energy component which is designed to reduce annual energy consumption is installed, resulting in more, not less, energy consumption in the first years after installation. Unfamiliarity of the resident(s) with the technologies new control capabilities is often the main reason for this. This is often exacerbated by a sudden need for the resident(s) to change the method they use to heat their home, meaning the new system requires more or less input from the user to reach and maintain desired comfort levels.

Furthermore, the residents' experience with the electricity storage heating system was negative, specifically in relation to cost for heating. This experience appears to have fostered a situation whereby the residents minimised the use of the electricity storage heating and reluctantly operated it in a manner to maintain an affordable energy bill. This, plus the perceived energy efficiency of the newer ASHP system, could explain the lower energy/heat demand before, then similar energy demand but higher heat demand, recorded after the ASHP installation. This is discussed further in Section 5.2.

5 Perception of ASHP and Comfort Levels

To complement and describe the energy data structured interviews were conducted on 3 occasions, these were conducted face-to-face, with the same resident on each occasion and with the full consent of the resident. The same set of open and closed-ended questions were asked approximately 12 months before the ASHPs were installed, then 6 months and 24 months after the ASHPs were installed.

Using a combination of standardised and well recognised building user survey (BUS) techniques, a short questionnaire was designed to capture the residents' opinions of the heating system, their perceived thermal comfort and profile the household for energy efficiency behaviour score (EEBS).

This robust technique provides the necessary qualitative data for benchmarking opinions and the behaviour for a small sample size such as in this study and prove useful when comparing changes within a person's environment (Stinson 2015).

5.1 Hygrothermal Comfort

Before and after the installation of the ASHP the residents were asked to score their comfort levels based on 3 criteria, Temperature, Indoor Air Quality (IAQ), natural Light levels, during the last visit the residents were asked additional questions which referred to the Noise made by the ASHP during its operation. Each criteria consisted of 2 or 3 criterion. The answers from all 4 participants have been averaged together for each period of monitoring and each criteria, the summary of those findings are presented in Fig 17.

Based on the recorded comfort scores and supplemented by the interviews the following findings are:

- All participating households reported that their comfort levels within the internal environment have improved considerably since the installation of the ASHP.
- When comparing the reported comfort levels before and after the installation of the ASHP all participating residents reported greater thermal comfort, meaning they were warmer faster and for longer.
- Similarly to their thermal comfort, all participants reported improved IAQ, meaning less visible surface condensation and lower humidity levels.
- Common complaints relating to discussions of internal temperature, air quality, ventilation and thermal comfort centred around the sensation of feeling cold in the hallway leading to the front door of the dwelling, with 2 of the 4 participants describing the front door as draughty and *'dragging the heat out of the house'*.
- Both before and after the installation of the ASHP each household's perception of the amount of natural light entering the dwelling was ranked as very comfortable. This criteria relates to solar heat gain and visible light.

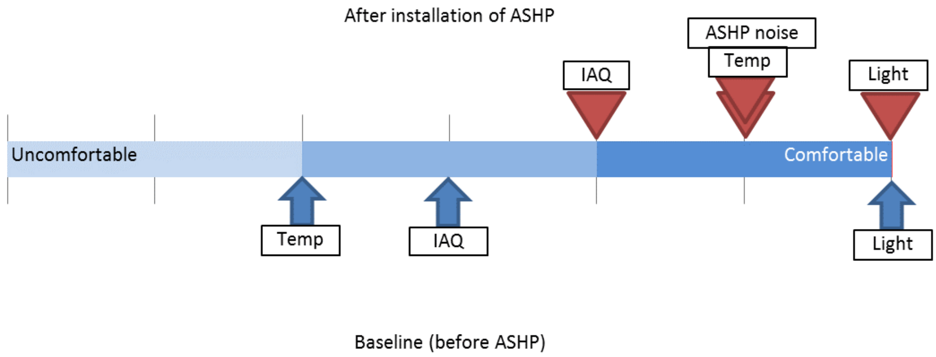

Fig. 17 Residents reported perception of internal comfort during the winter before and after installation of the ASHP

After the ASHP was installed a temperature and humidity logger was installed inside each participating dwelling. Fig 18 shows that the average annual internal temperature for each of the 4 households was within the recognised level of thermal comfort (17°C and 19°C). Monthly internal temperatures fluctuated between 15°C and 22°C for the 4 households. Internal temperatures before the installation of the ASHP are not available for comparison, however, the residents have reported that after the ASHP was installed the internal hourly and day to night temperatures are fluctuating much less and with less intensity.

Internal monthly relative humidity levels were recorded between 50% and 80%, which an annual average for all 4 households of between 56% and 67%, which are around the recognised internal RH levels for comfort. Although some higher readings (>70%) where recorded, none of the residents commented on signs of visual condensation, mould or uncomfortable humidity levels. Furthermore, all 4 participants commented on the noticeable disappearance of surface condensation and high level of morning humidity after the ASHP was installed.

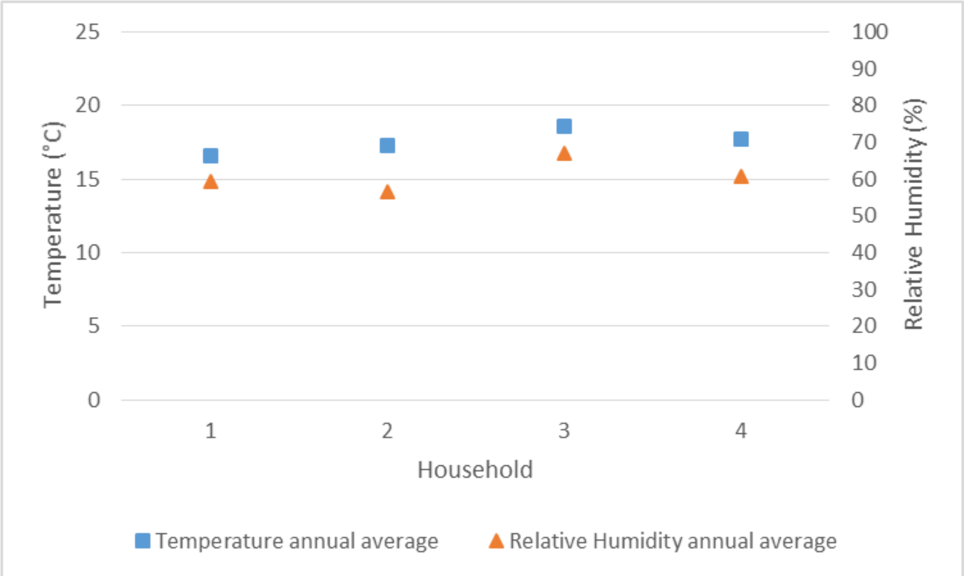

Fig. 18 Recorded internal temperature and relative humidity after ASHP was installed

5.2 Perception of ASHP

Six months after the ASHP was installed then repeated 18 months later, the residents were asked to comment on their perception of the ASHP and in comparison to the removed electricity storage heating the findings are as follows:

- The opinion of the residents towards the ASHP was on average were very positive, and did not change between the interviews conducted 6 months after ASHP was installed and 24 months after install
- The majority (75%) of participants reported that they have heard little or no noise coming from ASHP since it was installed
- All participating residents reported that the response time of the ASHP is much faster than that of the replaced electrical storage heating, meaning the house would begin to feel warmer faster.
- All residents reported that the controls for the ASHP are ‘much more’ intuitive than those of the old heating system. It was found that half of the participants had chosen not to change the pre-set temperatures and settings since the ASHP was installed.
- 1 resident reported that the electricity bills after the installation of the ASHP have increased considerably, by an estimated 73%. The findings presented in Section 4 have highlighted a considerable utility bill increase for this household which is related to the utility tariff.

The qualitative evidence showed that the residents where conscious of the costs associated with using the electricity storage heating to heat the home. Residents commented on the expense of the electricity storage heating and the feeling that they were not being sufficiently warmed for the cost of operating the system. This knowledge of operating costs appears to be the critical driver that led many of the residents to adopt more energy-saving habits specifically relating to heating, i.e. using jumpers and blankets when awake rather than using the heating. It appears likely that the electricity storage heating was not being used to meet all of the residents’ heating needs.

Conversely, the arrival of the replacement ASHP system was received by the residents as a more energy efficient and lower cost method to heat their homes. The majority of participants maintained that opinion 2 years after the installation. Each resident that participated with the interviews commented that the heating response time and user-controls of the ASHP were considerably better than the electricity storage heating. Furthermore, the resident(s) in each dwelling commented that they felt the internal temperature was considerably more comfortable with the use of the ASHP. 75% of residents commented that they were thermally more comfortable with the ASHP and content with their utility bill as they felt it more accurately reflected the heat energy they were receiving.

6 Conclusions

This report documents the quantative and qualitive findings of a 1 year project which set out to evaluate the performance of ASHP technology which replaced electricity storage heater in several properties managed by Ayrshire Housing.

The electricity consumption and utility billing information was obtained during the operation of the electricity storage heating and compared to that collected after the heating was replaced by the ASHP.

Synthesising the results presented in various sub-sections of this report the annual COP for the ASHP at the monitored dwellings was calculated as an average of 2.35, meaning that the ASHP generated over twice as much heat energy over the year for every kWh of electricity consumed.

Converting the energy consumption and generation figures it was found that the annual electricity bill for Household 1 after the installation of the ASHP was 32% higher than previous years, for Household 2 this increase was less at 3% in real-terms but still an increase.

Comparing Costs scenarios shows, and qualitative data suggests, that that the increases in utility bill cost maybe explained by the tariff situation and a confounding variable referred to as the rebound-effect.

The finding which shows the electricity being used by the ASHP is charged to the higher ‘all/day’ tariff as opposed to being on the less expensive ‘control’ or a comparable ‘low cost renewable’ tariff part-explains why the residents are paying more in their electricity bills. If the ASHP electricity was being charged at a lower tariff, similar to the that offered for the electricity storage heating, then the residents could benefit from the higher levels of heat generation; thereby satisfying preferred hygrothermal comfort levels at similar or lower cost than previous years when they used the electricity storage heating.

As the utility bill findings were not expected, given that the increased efficiency of the new heating system, namely COP of >2.0 compared to that of the storage heating (COP of 1) this lead the analysis to focus on comparable heat generation. Comparing all the energy data showed that the ASHP at both dwellings generated considerably more (99% and 82% respectively) heat during 2015 than was demanded on average during the years when the original (electricity storage) heating was in use.

One common theory for this type of finding is the so-called rebound-effect; where the expect benefits of installing a new low-energy system are inadvertently reduced because of changed energy-use behaviour of the user(s). Unfamiliarity of the resident(s) with the technologies new control capabilities is often the main reason for this. However, from the findings of this study it appears more likely that the higher-than-expected heat demand is more closely associated with the residents’ cost-benefit experience of the 2 different heating systems.

The evidence drawn from the residents showed that they consciously avoided using the original electricity storage heating to satisfy all their thermal comfort needs because of the expense of doing so. Whereas, the ASHP operated in a much more effective manner, and although costs were slightly lower than before, the ASHP was being used to produce much more of the residents' thermal need resulting in the higher heat demand profiles.

After the ASHP was installed a temperature and humidity logger was installed inside each participating household. When comparing the self-reported comfort levels before and after the installation of the ASHP all participating residents reported greater thermal comfort, meaning they were warmer faster and for longer. Also, the residents have also reported that after the ASHP was installed the hourly and day to night internal temperatures fluctuated much less and with less intensity. Furthermore, all participants commented on the noticeable disappearance of surface condensation and high level of morning humidity after the ASHP was installed. Which, in-part, explains the significant increase in demand for heat identified just after the ASHP was installed.

It is suggested that in order to reduce expenditure the occupants seek to obtain a utility tariff with a lower unit cost on the marketplace. Furthermore, the residents should become more familiar with the heating technology, which may occur naturally over time, but could be quickly improved through the use of simple, colourful, intuitive user manuals reinforced by home visits or tutorials.

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