Wimbish Passivhaus Development: Performance Evaluation
5 Year Assessment with Technical Appendix

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Synopsis

This paper assesses of the performance of the Hastoe Housing Association's Wimbish Passivhaus development for 5 years from June 2011 to June 2016.

It updates the Innovate UK (formerly the Technology Strategy Board) funded Building Performance Evaluation study that covered the period from 1st April 2011 to 30th September 2013.
(An executive summary and a case study may be found on http://wimbishpassivhaus.com/datasheets.html.)

This assessment confirms the study findings that the Passivhaus approach delivers homes that are comfortable, healthy, and economic to run. Recommendations are made to reduce the risk of future developments suffering from any 'performance gap'.

The continuing monitoring and assessment is valuable to confirm that there are no adverse performance trends, as well as to highlight any defects that might occur so that they can be remedied.

This version of the paper includes the Technical Appendix.

1. Introduction

The Innovate UK Building Performance Evaluation Study verified that the Wimbish Passivhaus development was meeting Hastoe Housing Association's (HHA) primary objective for the dwellings to deliver very low heating bills. Low bills help reduce the impacts of fuel poverty for their tenants, and have the potential to reduce rent arrears. An article in the CIBSE Journal[1] on the programme complimented Wimbish as "one of the few that performed well".

Figure 1: General View looking East: Houses to right, flats to left

The study proved that the Passivhaus approach delivers, and this assessment of the first five years confirms that it continues to deliver. Overall, the homes are performing largely as designed and provide the occupants, none of whom had particular prior interest in sustainability or energy efficiency, with homes that they find economic to run, healthy to live in and very comfortable and spacious for the size. Some residents stated that their heating bills were only £30 a quarter. This lack of a 'performance gap[2]' is a reflection of the high quality process necessary for Passivhaus development from design to occupation.

Content

This paper covers:

- Energy
  - Gas – total and seasonal use
  - Electricity
- Comfort
  - Thermal – winter and summer
  - Humidity – end of the winter
- Air quality – CO_2 readings in winter
- Ventilation – energy use by the MVHR in three properties.

1 See http://www.cibsejournal.com/general/home-truths-innovate-uk-building-performance-evaluation-programme-report/

2 For information on this concern see http://www.zerocarbonhub.org/current-projects/performance-gap.

2. Conclusions

The main findings from this assessment of 5 years of monitoring data[3] are:

- That the comfort levels achieved remain good throughout
- That the gas consumption, and thus the heating bills, have remained very low
- That electricity consumption remains 'normal', somewhat above the expected low levels in a Passivhaus.
- That the air quality remains good, however the ventilation systems are working a bit harder than they ought.

These confirm the Innovate UK study findings; no deterioration has been identified.

Some recommendations are made to help to ensure that future developments minimise the risk of a performance gap.

This assessment and ongoing monitoring is considered to provide valuable information on how these early (in the UK) Passivhaus dwellings are performing; this being of interest to Hastoe and for the house-building industry at large.

Reaction from households:

"Since moving in 2011, my flat is wonderful. It's light and airy and very peaceful. You wouldn't think that we live on an estate "

"We have been very comfortable and have enjoyed a constant pleasant temperature. The brise - soleil has done its job beautifully, as have the exterior window blinds. It is a pleasure to have such large windows and triple glazing is most effective both in terms of temperature and noise levels."

"Light has been fine as I can adjust accordingly. Temperature can be quite warm if blinds are left up by accident whilst at work. Easily rectified by opening doors and windows to get air through home."

"Our gas bill is significantly less. As cooking.etc is by electricity we have not noticed a change here, or with our water bill."

"Utility bills are much lower, even water bills have been reduced. Gas is very low although we are still being charged by companies for the 'standing charge'."

"Because of the design of the flats / houses my bills are very low."

"Because of the airflow system I think it makes you feel better."

"Clearly living here made me much happier and I feel I can give something back to the community."

"We are happy and content and benefit from the air quality and so much natural light."

[3] The monitoring has continued beyond the 2 year Innovate UK funded period in order to gather valuable additional data. Albeit there is no funding to fix any monitoring faults which might arise, and some metering has been discontinued as the equipment was an inconvenience to the residents.

3. Energy

Annual Gas Consumption

Expectations

Passivhaus design aims for a reduction in space heat demand of around 80% from existing housing stock; reductions from new property built to current UK Building Regulations remains large. Compliance with the Passivhaus standard requires that space heat demands no more than 15 kWh/(m^2·a)[4] of heat; all 14 dwellings at Wimbish were designed to comply with this requirement (the flats as a single unit).

The design also aims to keep hot water consumption low.

At Wimbish, space heating and hot water are provided by a small gas boiler in each property, supplemented by a solar thermal panel; all hot water and heating is provided via the thermal store. Gas is not used for any other purpose.

The assessment compares actual gas consumption of each property with the figures calculated in the PHPP[5] design.

Findings

Even the worst performing house at Wimbish continues to consume far less gas than typical properties.

Consumption in a property varies from year to year, reflecting the weather. There have been changes in consumption in a couple of properties following a change of tenant.

Overall, except for the colder winter of 2012/13, average performance is close to the expectations. There is variation between households as one might expect; and we can seek to explain this by the level of occupation and the habits of the household.

If the households were on a cost-effective tariff, then the average annual gas bill in the flats was assessed as being £62 and in the houses £130 (including VAT). This was for 2014, other years would give similar figures.

[4] For example, for an $80m^2$ property, this is only 1,200 kWh of heating in a year (nb hot water demand must be added)

[5] The Passivhaus House Planning Package – Wimbish was designed using the 2007 release.

Detail

Figure 2 shows the annual gas consumption of the properties since occupation. It shows how this varies from year-to-year and how it differs from one property to another.

Five bars are shown for each property, one for each year of occupation (from 1st July to 30th June).

The second year, 2012/13, was the only hard winter experienced, the others being a little milder than average; the chart clearly shows the extra consumption in the second winter.

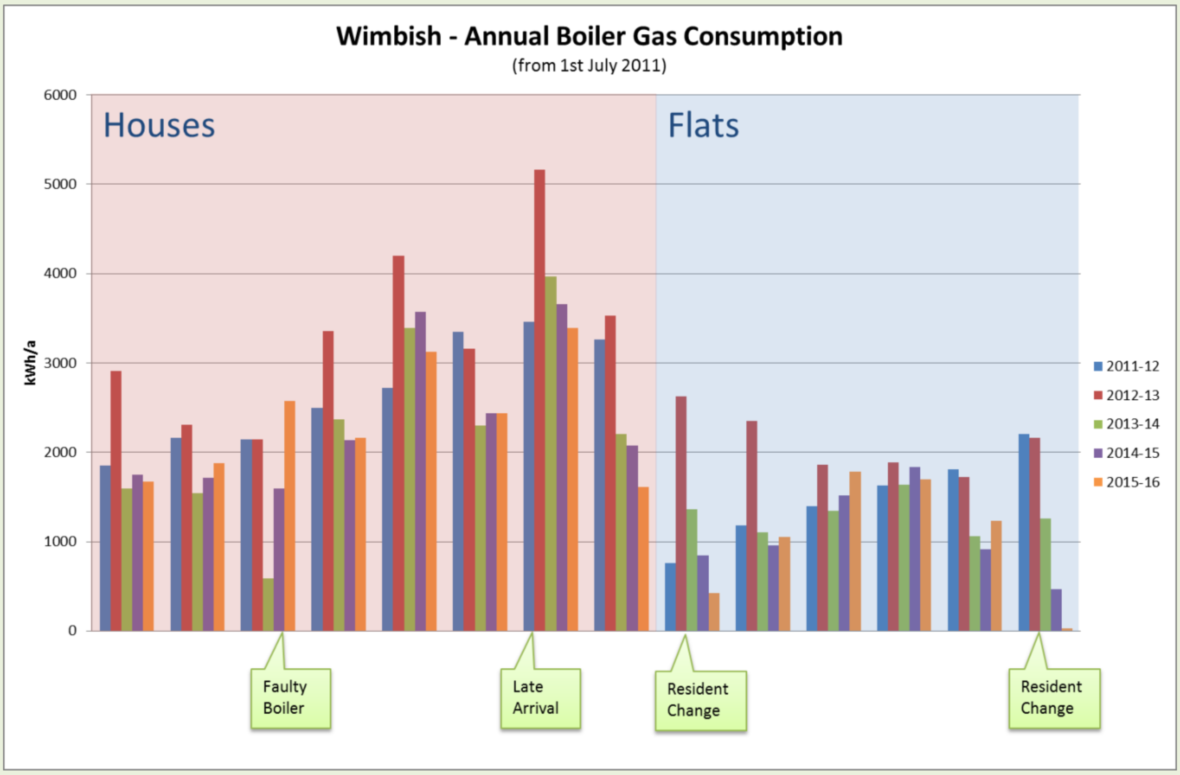


Figure 2: Annual Boiler Gas Consumption

To put this into context, Figure 3 compares these same figures with Ofgem's typical domestic consumption values (from 2013); it illustrates just how low the Wimbish consumption is.

The chart also illustrates roughly how much the Wimbish residents would be paying for their gas if they were on Ebico's Equigas tariff. During our Innovate UK study this flat rate tariff was identified as probably being the most cost-effective gas supplier option for Wimbish – it should be noted that very low consumers of gas are penalised by most suppliers in having to pay more per kWh delivered than standard customers[6].

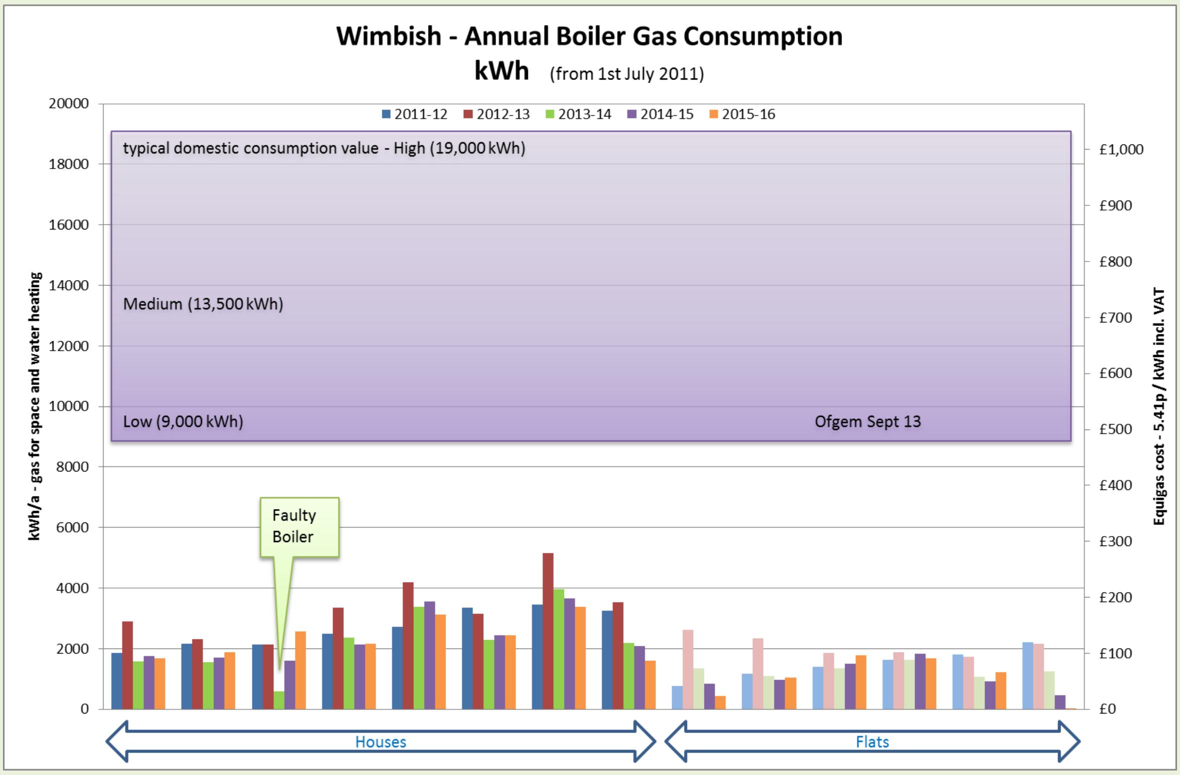


Figure 3: Boiler Gas Compared to typical values

6 Either through the standing charge, or by paying a higher tariff for the first 'X' thousand kWh – a threshold likely to be higher than the quantity consumed in a Passivhaus.

Figure 4 shows the gas consumption normalised by the floor area of the properties. In addition, for comparison, this shows the expected boiler gas consumption calculated by PHPP, the Passivhaus Planning Package used for design.

Overall, especially if one overlooks the data from the colder winter 12/13, the average performance is close to the expectations[7]. There is variation between households as one might expect; and we can seek to explain this by the level of occupation[8] and by their habits[9].

It can be seen in the two flats that have changed hands, that the new occupants have been more careful than their predecessors, though they are perhaps trying too hard to reduce already low gas bills[10].

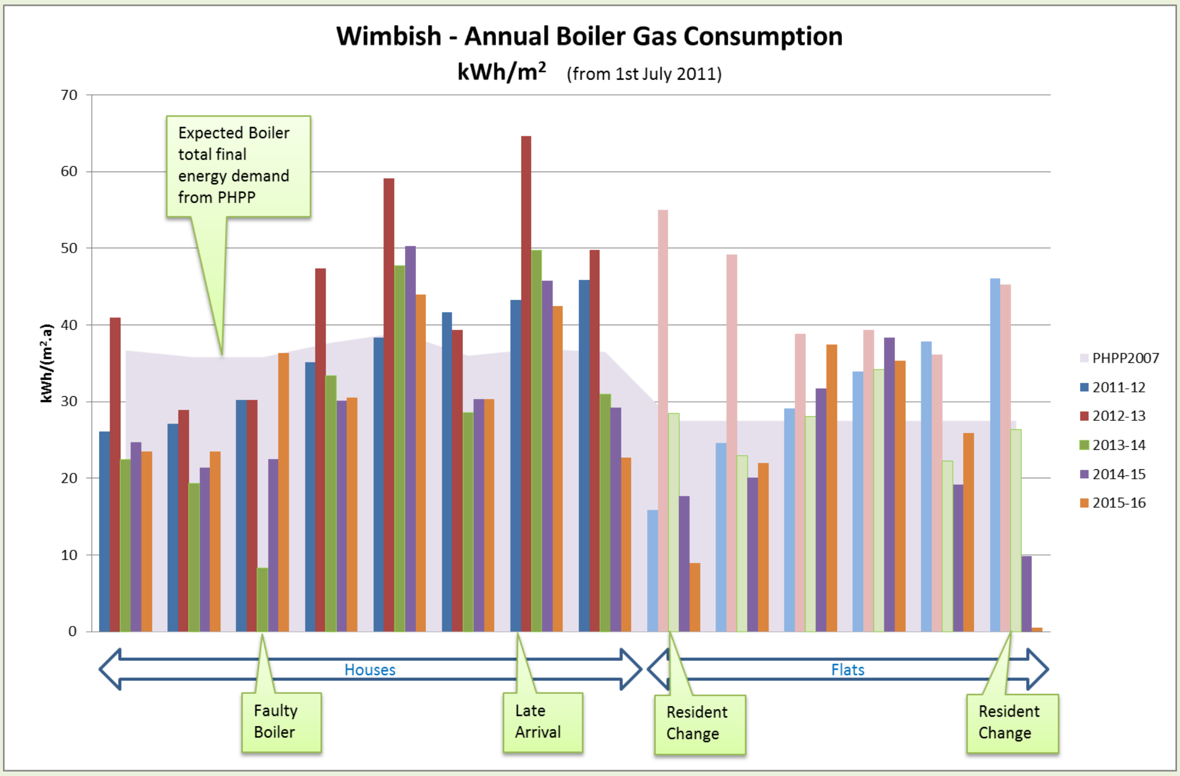


Figure 4: Boiler gas consumption by floor area

7 Note that data has not been adjusted for the actual weather.

8 The heat demand of a Passivhaus is so low that even the heat given off by an additional person can make a difference.

9 Heavy use of appliances, for example, would generate heat and reduce the need for gas.

10 Or they might be suffering from an undiagnosed technical issue with their boiler or MVHR.

Seasonal Gas Consumption

Expectation

In a Passivhaus, the space heating is only required in the coldest months, whereas hot water demand is fairly constant throughout the year. The grey bars in Figure 5 are the sum of these two demands and the yellow bars show the contribution from the solar panels towards meeting this demand.

The boiler is required to make up the difference between demand and the solar contribution.

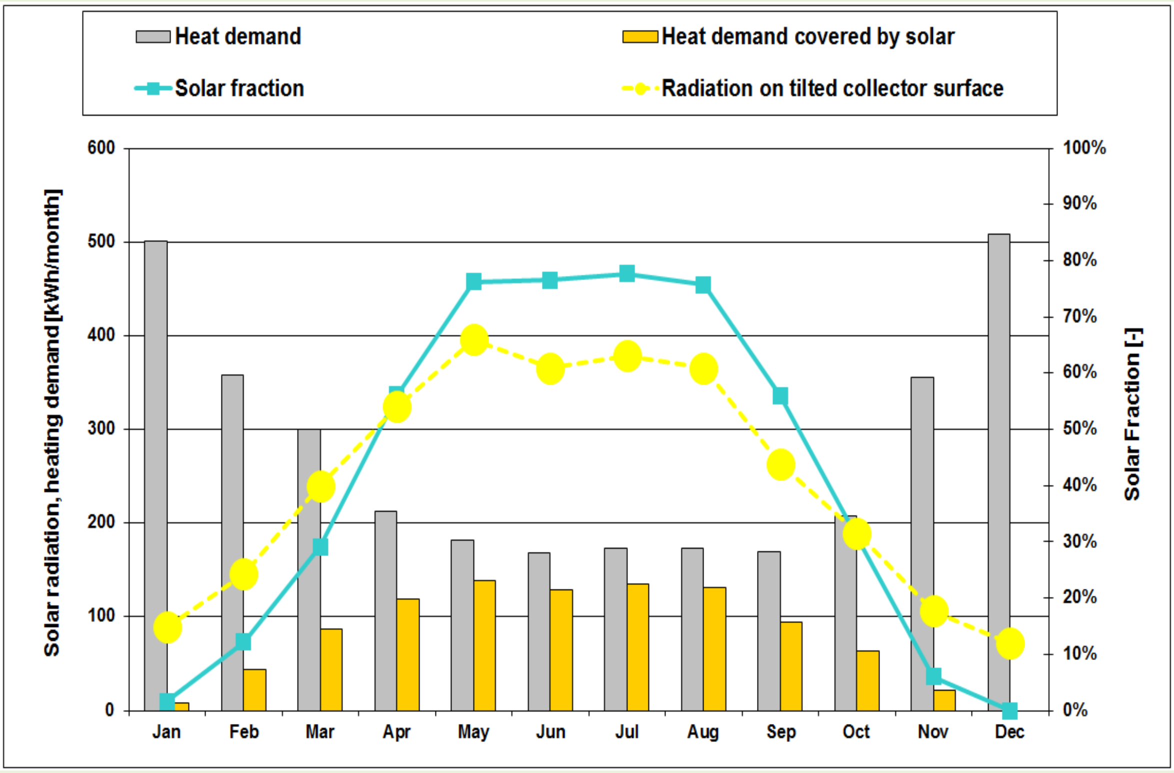


Figure 5: Heat Demand and Solar Contribution (3-bed house as designed – but re-implemented in PHPP8.5)

Thus, if the properties are performing as designed, we might expect to see high gas use in December and January (up to 500 kWh per month), falling to very little from April through to September, the expectation being no more than 30 kWh per month[11]. Indeed, in some properties, summer gas use was expected to be zero[12].

Findings

However, as can be seen in Figure 6, around half of the properties for which we have data, have summer gas consumption well above the expected values.

Site visits to review the provision of hot water were made autumn 2014 and remedial action reduced consumption in the worst properties in 2015.

11 The same solar panel is used in all properties; the figure shows the 'worst-case' scenario

12 Where the occupation level, and hence use of hot water for bathing, is low

A recommendation from this is for future design to consider the impact on systems and their performance if occupancy levels differ from the Passivhaus norms. At Wimbish it would probably have been desirable to have larger solar panels on the houses.

Detail

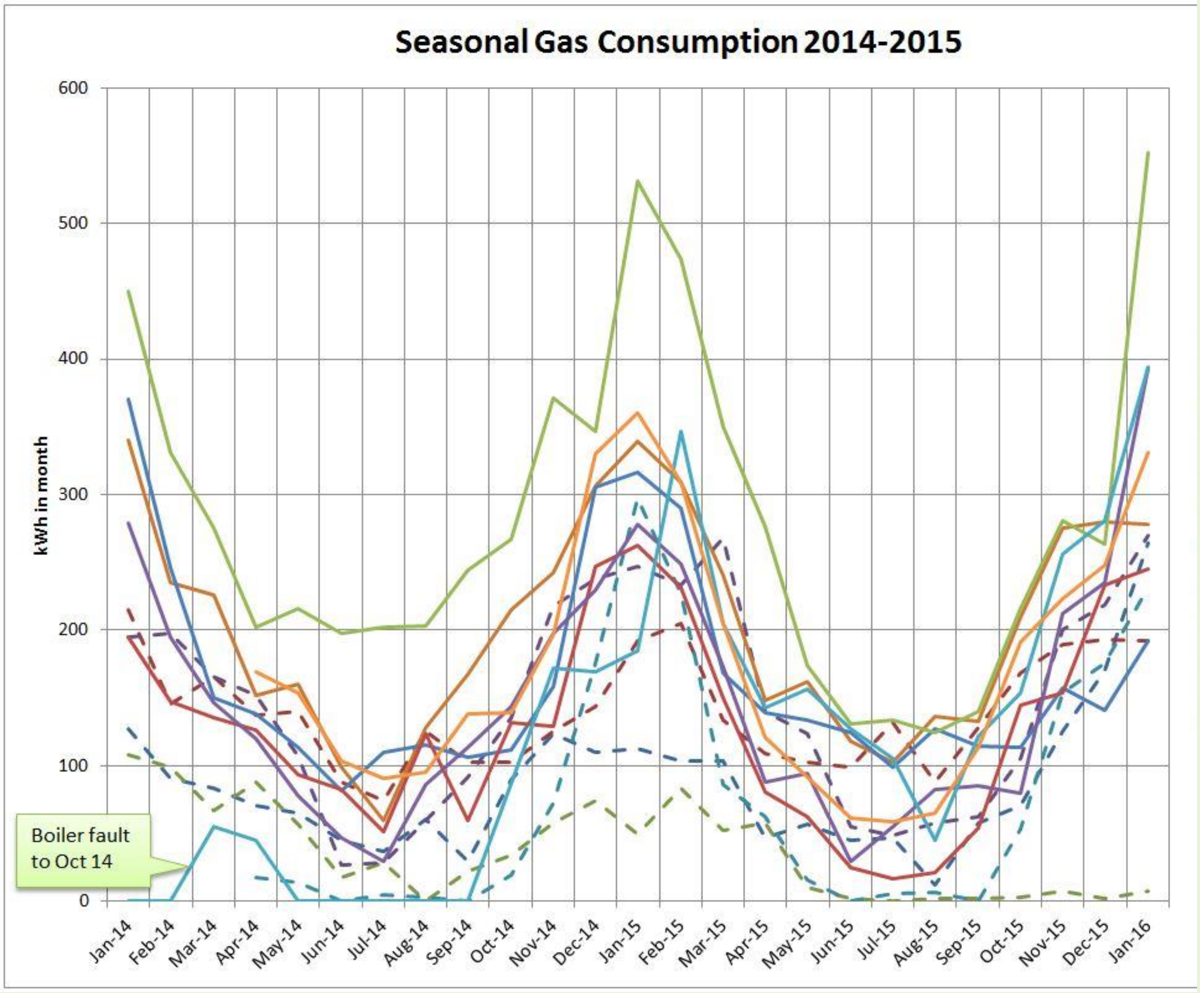


Figure 6: 2014-15 Monthly Gas Consumption[13] (houses solid lines, flats dashed)

This unexpected gas use in summer (greater than 30 kWh per month) may be down to one or more of the following:

1. Unanticipated (and unlikely) use of space heating[14]
2. Reduced, or no, contribution from the solar panels.
3. Household sizes are larger, and/or the residents bathe more, than the assumptions in PHPP
4. Excess heat losses from the thermal store and pipework.

[13] Gas metering for 2 plots has not functioned, and in a further two only since end March 2014.

[14] Some ‘accidental’ summer heating has been detected in previous years, however heat usage was insignificant

Annual Electricity Consumption

Expectations

The Passivhaus standard does not include an explicit target for electricity use, but we can establish an allowable figure[15] for electricity for each property – about 27 kWh/(m^2·a) for the houses and 31 kWh/(m^2·a) for the flats.

By comparison, if we divide the Ofgem medium typical domestic consumption value by the average UK property size, we get a figure of 40 kWh/(m^2·a).

Findings

In general, the electricity consumption in the houses may be described as ‘normal’, rather than the reduced level hoped for in a Passivhaus. In the flats consumption is less, a reflection of lower numbers of occupants.

Extra heat gains from higher electricity use will tend to reduce gas bills for heating in winter, and raise the risk of overheating in summer.

Ideally a Passivhaus developer would provide energy efficient appliances. Designs might also seek to encourage energy saving behaviours, and handover to the residents should also include tips on reducing their electricity bills.

This reinforces a recommendation that designers should consider the sensitivity of their design to variations in factors such as level of occupation and use of appliances.

15 By deducting the gas usage from the primary energy target of 120 kWh/(m^2·a).

Detail

The annual electricity consumption chart (Figure 7) shows that on average the houses consume a little above the Ofgem medium value, and the flats well below – largely a result of lower level of occupation.

There is a distribution of consumption across the houses and across the flats, rather more in the flats – again reflecting occupation levels. In most properties, there is little year-on-year variation in consumption, the exception being 2 flats that changed tenants.

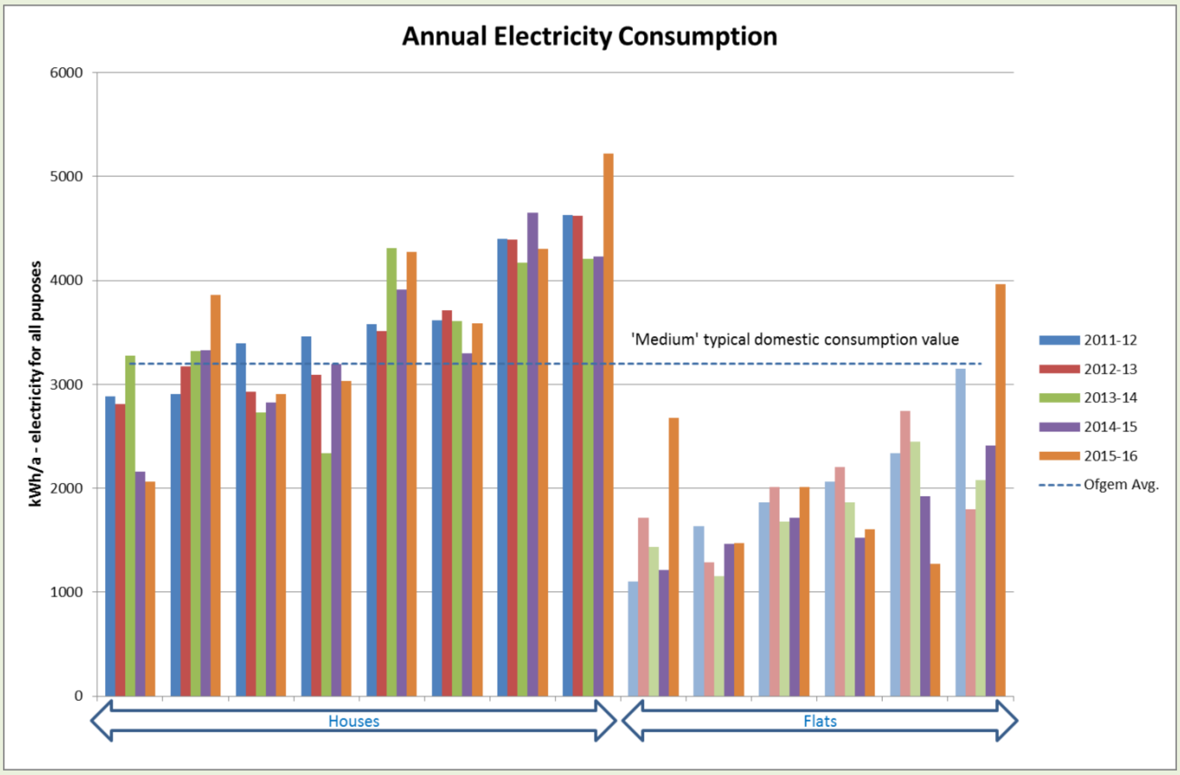


Figure 7: Annual Household Electricity Consumption

Plotted against floor area, and in comparison with the PHPP 'allowance' (Figure 8), it can be seen that none of the houses, and only two of the flats, are meeting expectations.

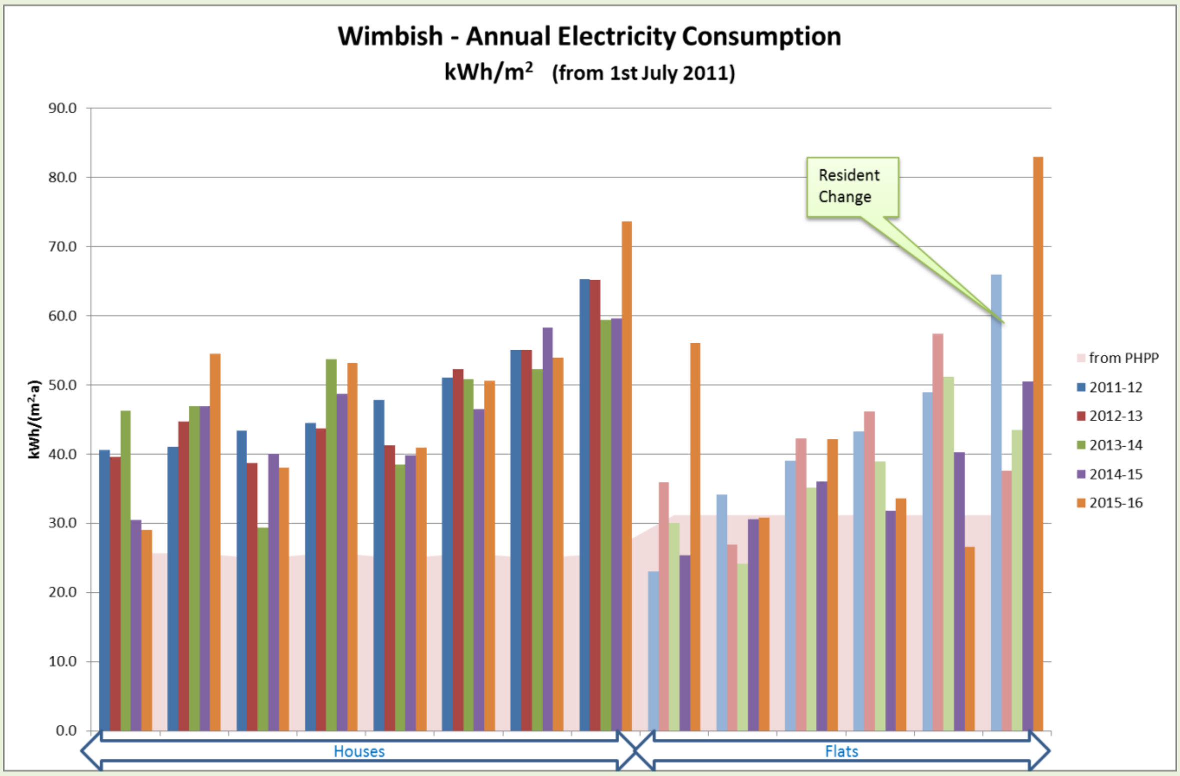


Figure 8: Electricity by Floor Area

This 'normal' electricity consumption may be attributed to two factors:

1. Higher levels of occupation than assumed in the design
2. Households bringing their existing, relatively inefficient, appliances with them; and, where new appliances were purchased, the capital cost being a higher priority than efficiency in use.

4. Comfort

Thermal comfort in winter

A Passivhaus should be capable of maintaining a constant temperature of 20 °C in cold weather, however, in practice, the occupants may be happy to let the temperature fall a little when they are out, or asleep. Some households choose to maintain a higher temperature, recognising that it costs them little extra to do so.

Figure 9 shows, for February in 2014, 2015 and 2016, the range of values for 80% of the time[16], and the median value, for each sensor[17]:

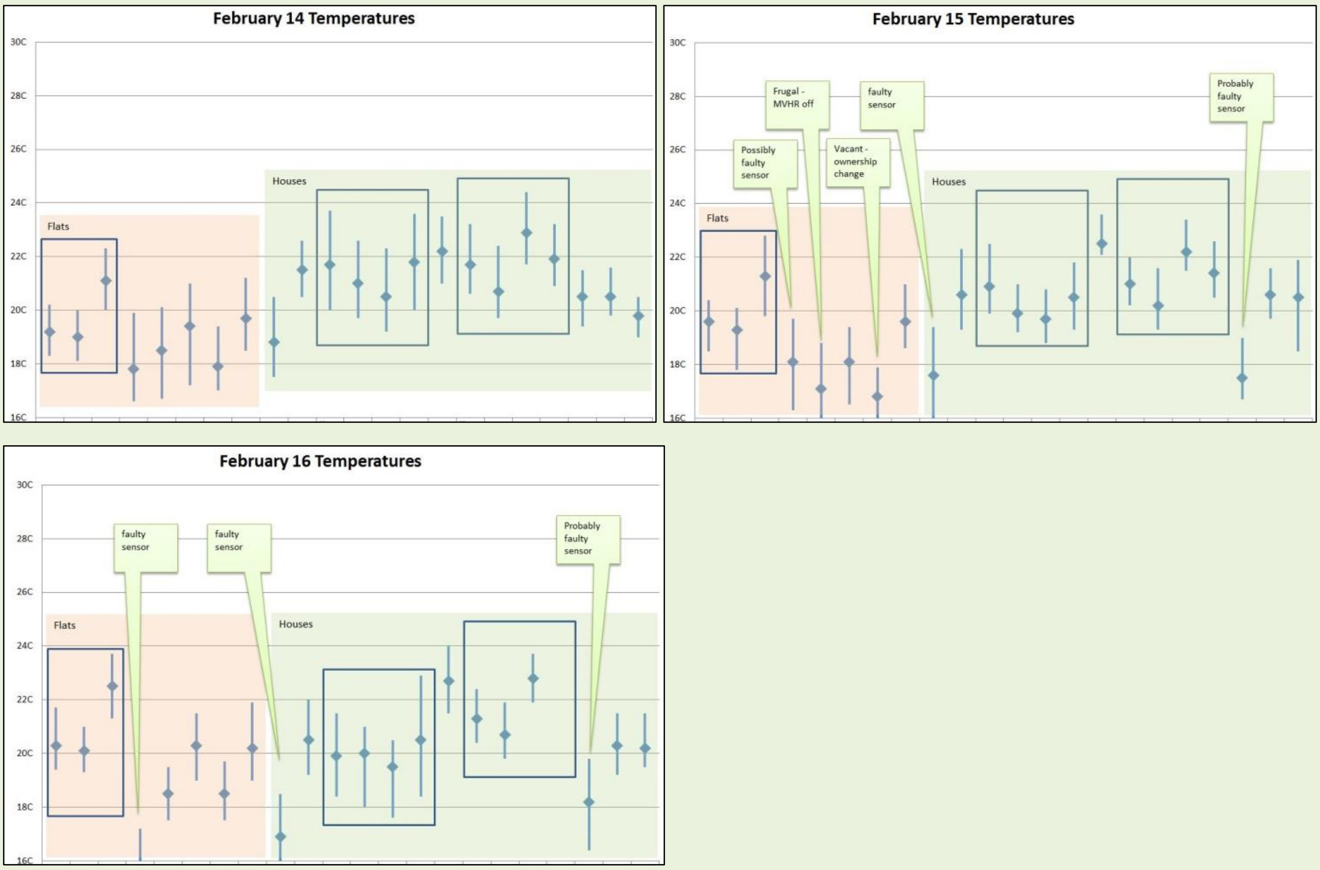


Figure 9: Winter Temperatures (groups show sensors in one dwelling)

The flats are generally a bit cooler than the houses; this is thought to relate to the level and hours of occupancy rather than any inherent difference in the structure.

Overall, the temperatures in February are good, though it should be noted that they were relatively mild months.

16 Omitting highest and lowest decile

17 Close inspection of the readings, taken at 5 minute intervals, is employed to confirm faulty sensors (failing sensors can work intermittently). Unfortunately there is no budget to replace them.

Thermal comfort in summer

There is concern that new homes, especially thermally efficient ones, can overheat in summer when it is difficult to dissipate excess heat.

The aim of Passivhaus design is to ensure that 25 °C is not exceeded more than 10% of the (annual) occupied hours.

Although 2014 and 2015 were warm years overall, they did not have an extended period of hot days that would thoroughly test the dwellings and their occupants. July was the warmest month; Figure 10 shows that most properties average below 26 °C for the month, though some are warmer than many people would find comfortable. That some households are able to keep cooler shows that it is possible.

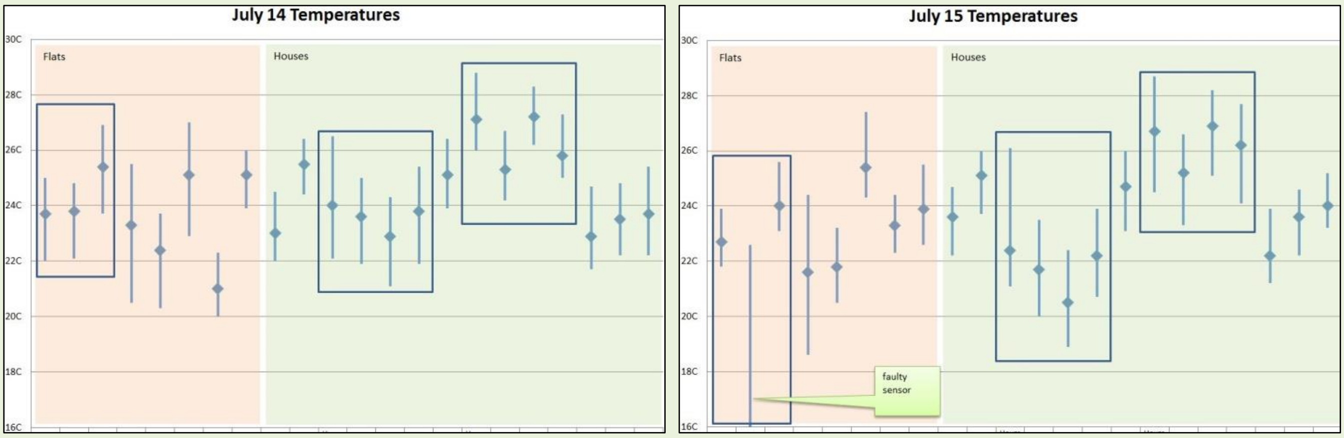


Figure 10: Summer Temperatures (groups show sensors in one dwelling)

Over the whole of 2014 and 2015, all but three of the properties were comfortably within the '10% of the time' limit. The worst exception is a 3-bedroom house:

	South-facing kitchen	Bedroom
above 25 °C in 2014	59%	47%
above 25 °C in 2015	56%	41%

This property has the highest occupancy, likes it to be warm, has high electricity use, and a reluctance to open windows because of insects. (this is the house that was hottest in July each year.)

Humidity

The air flows required in a Passivhaus are designed to be sufficient to remove the risk of excess relative humidity (RH) and consequent condensation and mould[18], so long as the MVHR system has been constructed, commissioned, maintained and operated correctly. Our Innovate UK study analysis found that values have stayed well below upper RH thresholds.

There is also a risk that, by the end of the winter, a mechanically ventilated property might become overly dry, with the potential for respiratory difficulties for susceptible occupants.

The standard heat exchanger in the MVHR unit can be replaced by one that also recovers humidity. A trial in winter 2013/14 of such an 'enthalpy exchanger' was conducted in the two houses that have MVHR monitoring in place.

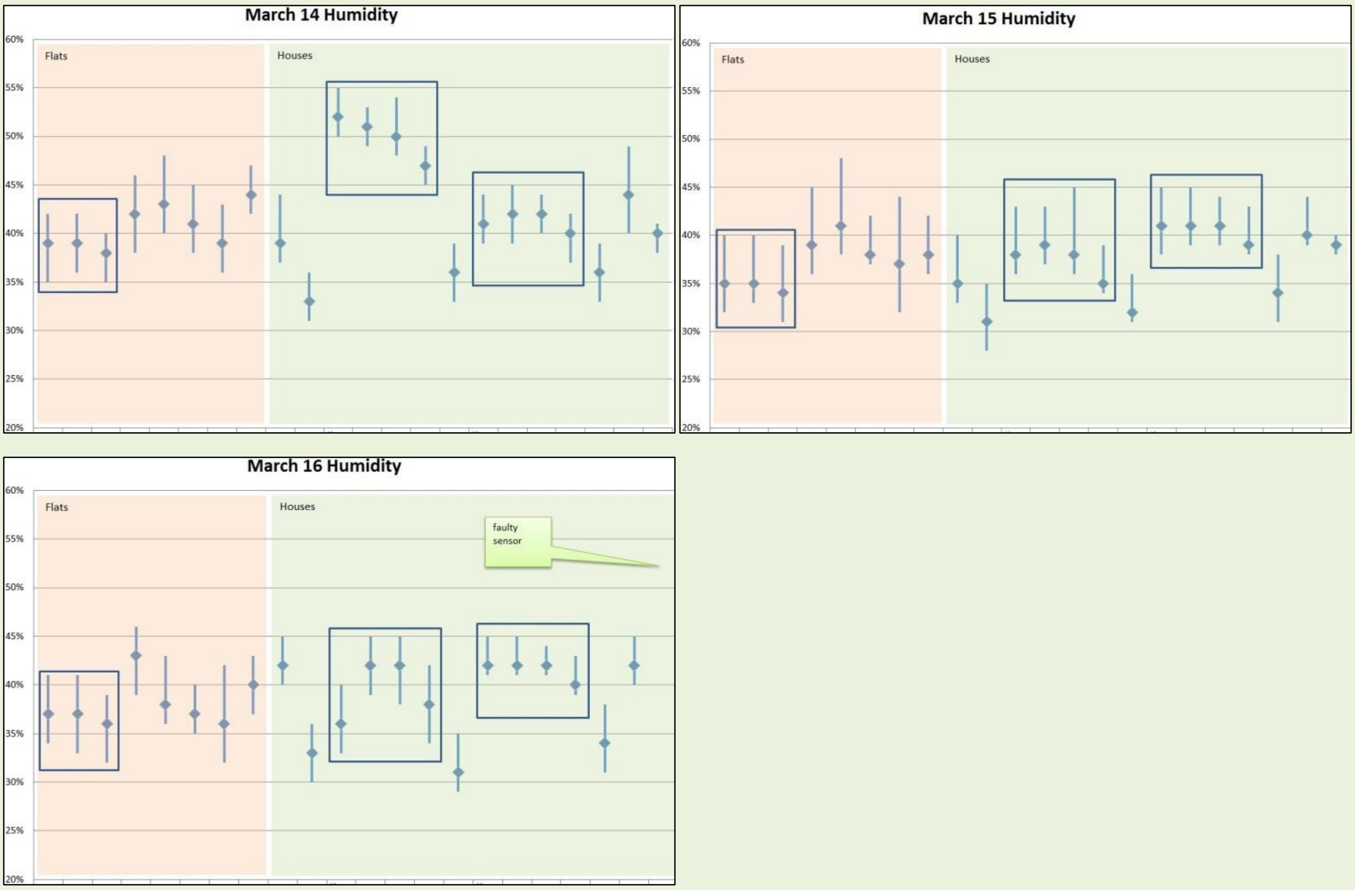


Figure 11: Humidity Distribution End Winter (groups show sensors in one dwelling)

The above charts show that for each sensor the values are within a narrow band.

The four sensors with the highest RH values in 2014 are all in one 2-bed house, the one with the enthalpy exchanger. In subsequent years, after the trial, the values were more 'normal'. The 3-bed house with the same exchanger does not show the same increase.

Overall the RH levels are perfectly acceptable, and are not becoming over-dry.

18 In addition, high levels of insulation and avoidance of thermal bridges prevent cold spots.

5. Air quality

Carbon dioxide levels are commonly used as a proxy for the air quality in a property. In an occupied room with poor ventilation, the CO_2 levels can quickly rise from an ambient 400ppm to 2,000ppm and above, where occupants' concentration levels diminish and fuzzy-headedness starts. While absolute thresholds are difficult to quantify, value excursions above 1,500 should be infrequent, and it is desirable to keep peaks to no more than 1,200ppm[19].

The Innovate UK study found that readings at Wimbish were generally in the acceptable range, although air quality could be impacted when the filter needed changing. This assessment confirms that the air quality remains acceptable. Figure 12 illustrates a typical daily cycle of readings in the three properties we are monitoring (over a week in winter when windows are less likely to be open).

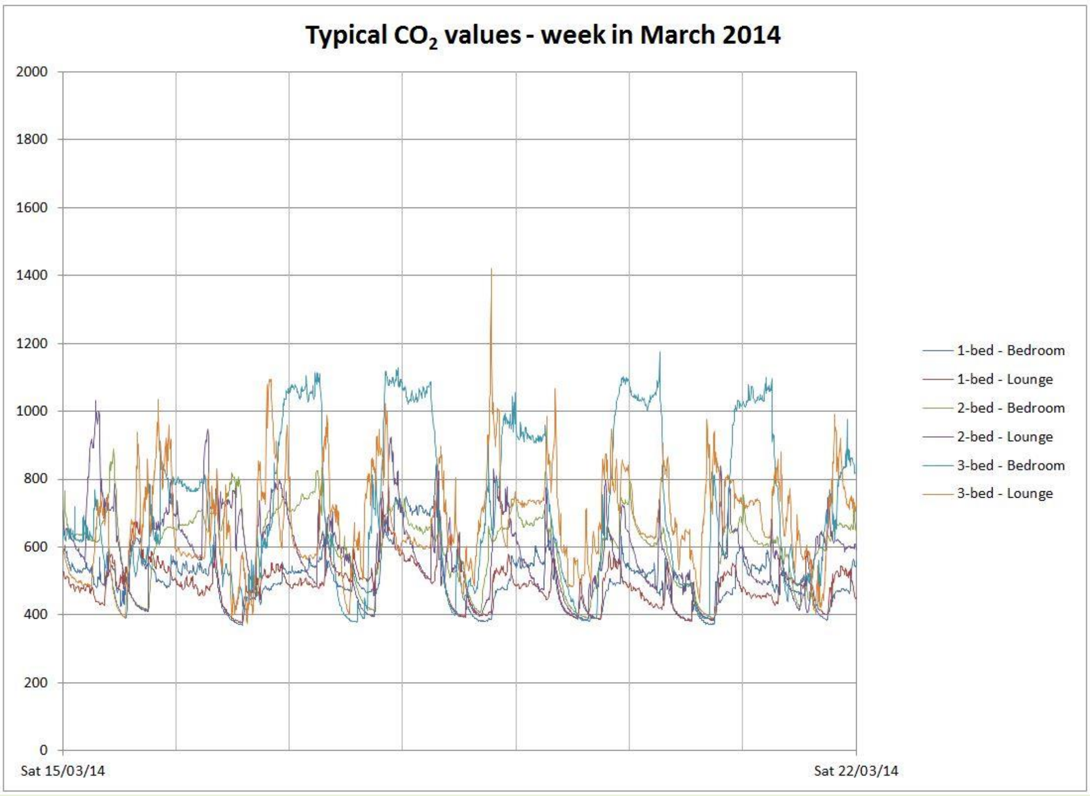
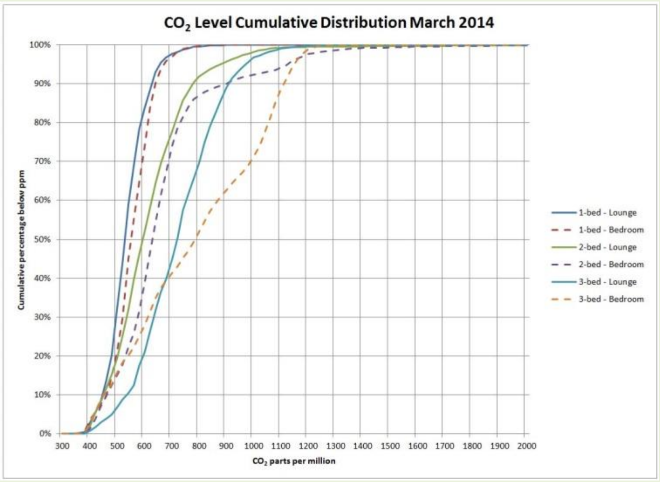
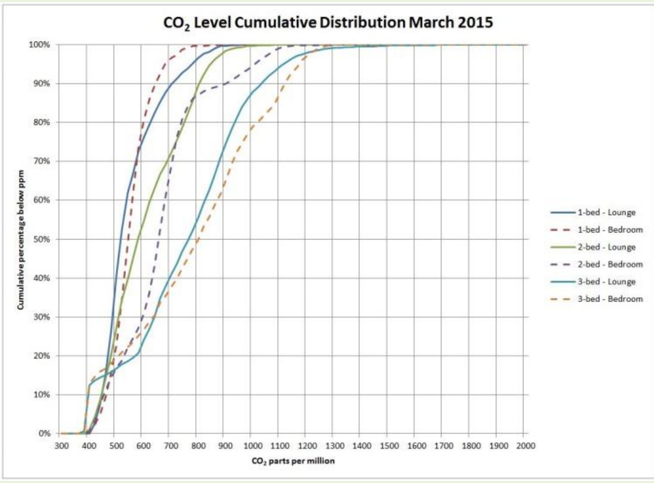


Figure 12: Typical Carbon Dioxide readings

[19] On the other hand, keeping peak CO_2 levels below 800ppm could be indicative of too high an air exchange rate [the greater the air flow the more energy used by the fans, the greater the heat loss by the system, the faster the moisture loss, and the faster the filters block up].

During the summer months, when occupants are more likely to open windows, the air quality is less of an issue; thus looking at data in March is likely to be indicative of the worst figures[20].





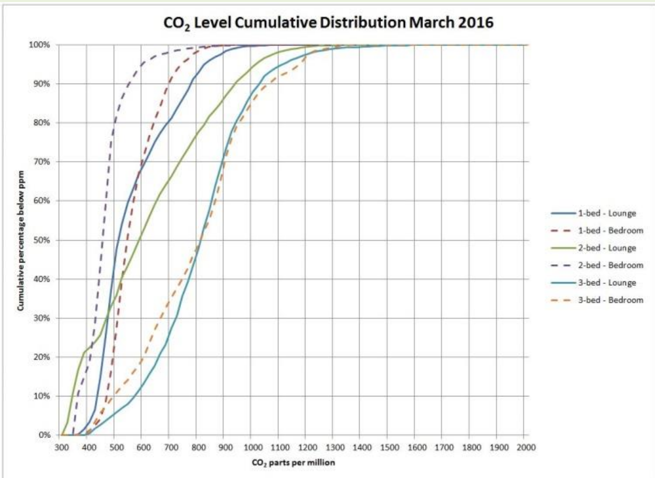


Figure 13: Distribution of Carbon Dioxide readings in March

CO_2 levels are good, only very rarely above 1,200 ppm.

The MVHR were commissioned to the Hastoe-expected occupation levels for the property types. This probably explains why the under-occupied flat performs best, followed by the 2-bed house, then by the over-occupied 3-bed house.

It should be noted that the wired sensors were fitted in the second bedroom in the houses (the master bedroom was specified). In the 2-bed house this is irregularly occupied; whereas in the 3-bed house it has been occupied by several children.

20 This analysis is for the whole month. Looking at 'occupied hours' for each room might be more meaningful (but 'occupation' is not being explicitly monitored).

6. Ventilation

The ventilation system must maintain air quality (section 5) and contribute to maintaining comfort (section 4). It must do these efficiently:

1. In the energy used to run the fans
2. In the level of heat recovery achieved
3. And the effort/cost in maintaining the filters.

Our Innovate UK study found that under normal operating conditions the fan electricity consumption and specific fan power (SFP) were close to the product specification in the monitored flat and 2-bed house, but that the fans were working a bit harder in the 3-bed house, increasing the SPF by about 1/3 – however, in all three cases the systems remained within the Passivhaus allowable limit.

Monitoring the energy used by the fans each day provides a useful indicator of the status of the filters.

Property	Nominal Fan Watts	Image	Equivalent daily 'pulses' (each pulse being 0.1 kWh)
2-bed House	29	Figure 14	7
3-bed House	54	Figure 15	13
Flat	25	Figure 16	6

The reduction in daily consumption in July 14 seen in Figure 14 is suggestive of a filter change, and the short term reduction in September of the residents taking a holiday.

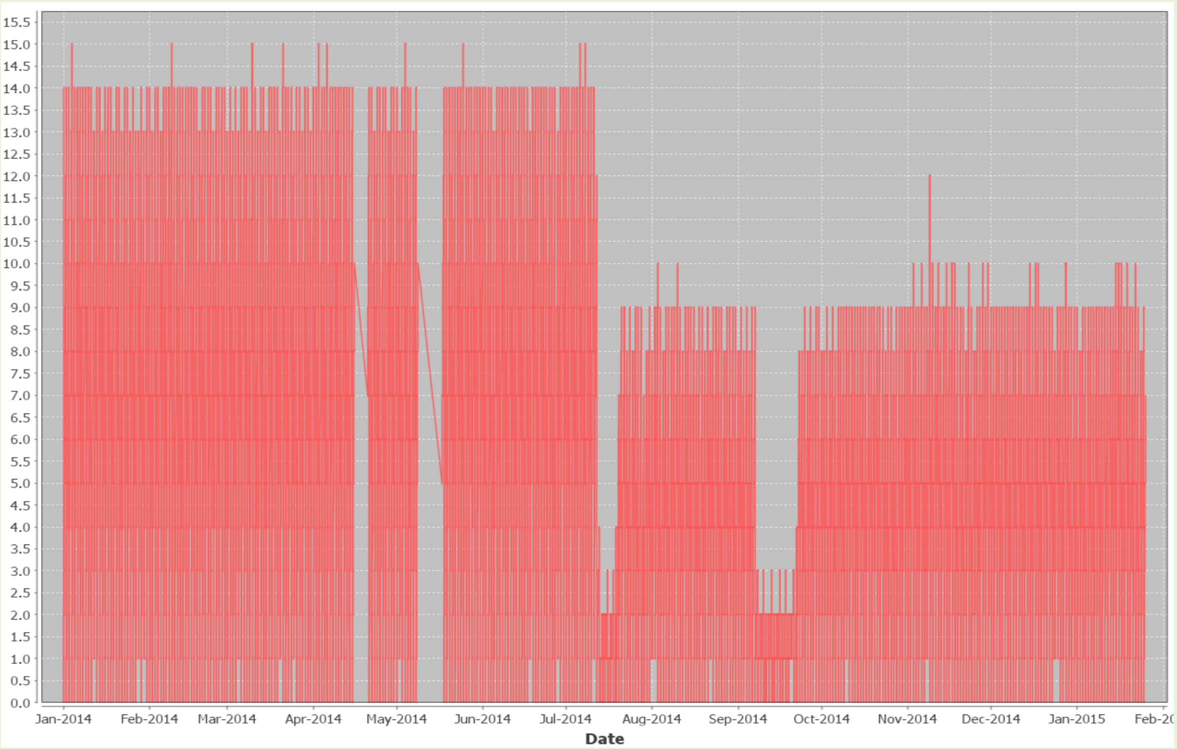


Figure 14: 2-bed House MVHR Electricity Consumption

The filters catch pollen and other particulates in the incoming and outgoing airflows before they reach the heat exchanger and the fans, thereby protecting these components from clogging up. The filters on the incoming air also reduce the quantity of dust build-up in the ducts (otherwise they would need periodic cleaning) and ensure good air quality for the residents.

Over time the filters will become blocked, to maintain the airflows the fans will start to work harder, and noise levels will increase. If the filters are not replaced then eventually the fans will reach maximum speed, and the air flow will then become compromised and probably unbalanced, affecting air quality and humidity levels, and the ability to deliver heat. Running at full load may reduce the life of the fans. Filters should be replaced when the fans start to work harder.

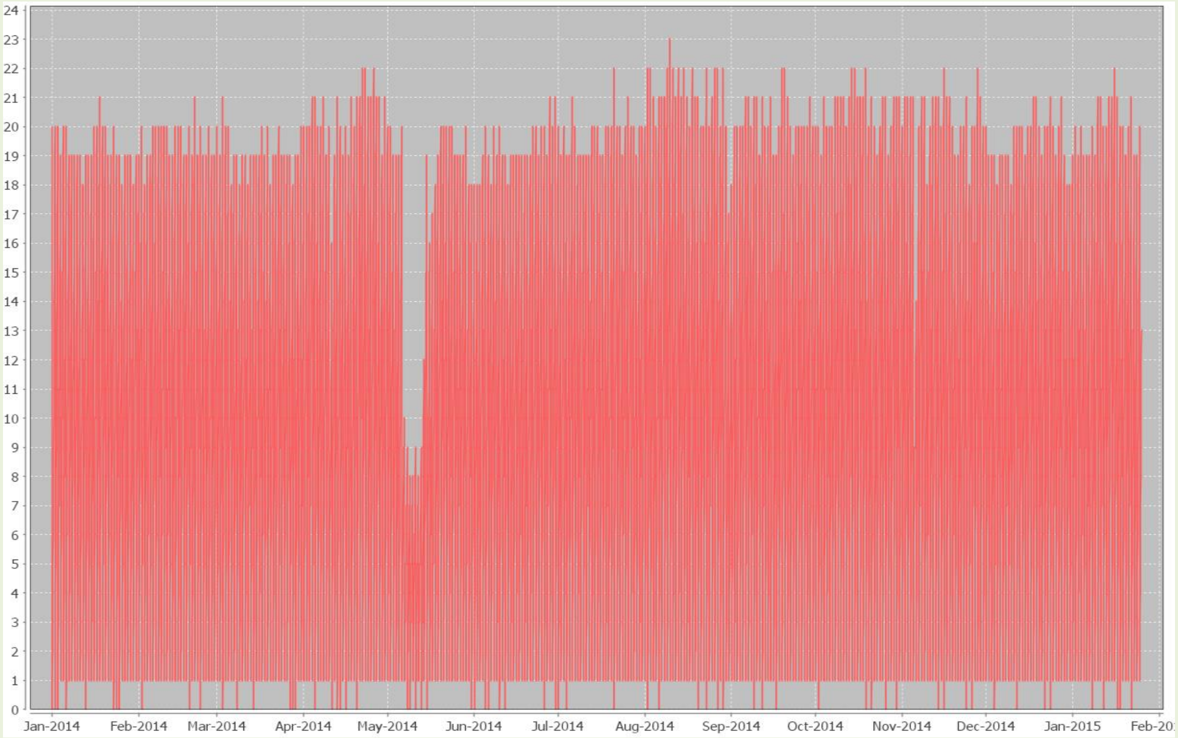


Figure 15: 3-bed House MVHR Electricity Consumption

These three figures do not show evidence of the filter changes as clearly as similar charts produced for the Innovate UK Study; they do show that daily electricity consumption in the houses[21] is well above the nominal level, implying that the filters need changing, although we understood that they have been changed. The issue is complicated in that both the houses employed the enthalpy heat exchanger as a trial for part of the year. It was expected that these might increase the fan load; however the end of the trial is not evident in these figures.

[21] As the same MVHR units are employed in all the properties, those in the flats are running at the low end of their range, this gives them a lot more headroom before any adverse effects are evident.

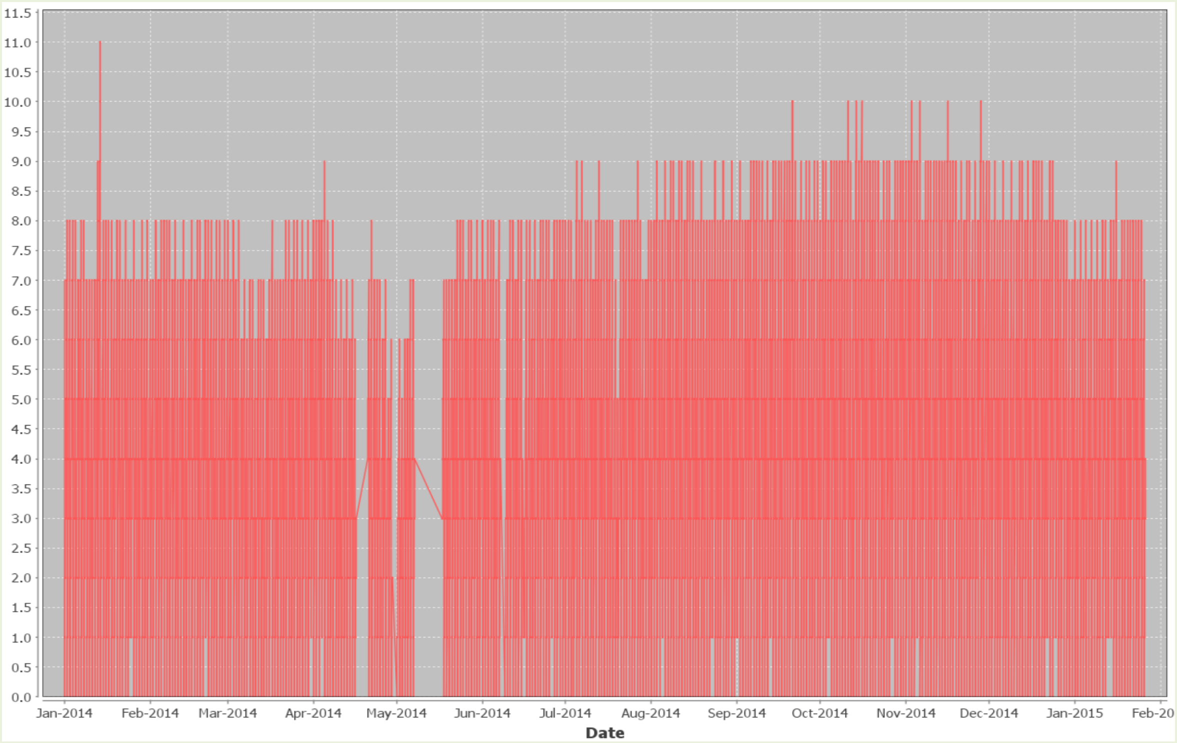


Figure 16: Flat MVHR Electricity Consumption

Property	Innovate UK Study: Nominal consumption kWh/a	Innovate UK Study: Actual year to 5/7/13 kWh/a	2014 kWh/a	2015 kWh/a
Flat	219	223	291	363
2-bed House	254	353	405	659
3-bed House	473	634	715	768

The increase in consumption is a concern; it may just be confirmation that the filters really should have been changed sooner, or it may be symptomatic of some other malaise. Either way the households will have had higher electricity bills as a result, and there might have been some impact on the air quality and on noise from the unit.

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A. Appendix – Performance considerations in a Passivhaus

Passivhaus design is holistic and seeks to consider a wide range of factors that may have a bearing on performance. As background to the charts and discussion in this paper some of the issues are briefly discussed here.

A Passivhaus is expected to require very little heat input; at Wimbish, with solar systems to meet a large part of the hot water demand in summer, gas consumption by the boilers is very low. Passivhaus design also aims to keep electricity use down by provision of energy efficient lighting and, if possible, by providing efficient appliances. It is assumed that occupants will be sensible in their use of appliances (perhaps as a result of handover advice). Thus primary energy demand is kept low, along with the resultant carbon emissions. This is calculated from an assumed level of occupation, derived from the considerably more generous German standards for space per person than the figures applied for UK social housing (and indeed any UK housing) [22].

If the level of occupation, both numbers and hours, is higher than the design expectation then it is likely that more hot water will be used, as along with an increase in appliance use. Not only will the latter increase electricity consumption, but, at least in winter, the heat gains from these uses may reduce the need for space heating. Lower occupation, more likely in the flats, can have the reverse effect.

That most households brought their existing appliances with them, and purchase new with cost price as the primary consideration, means that most appliances are not the most efficient on the market. This too raises electricity use and may impact heat demand.

A Passivhaus is designed such that it is capable of maintaining a constant temperature of 20 °C. In practice, households are likely to find some variation of temperature pleasing. Inherent in the high level of thermal insulation of a Passivhaus is that very little heat can be lost through the fabric, and left alone with the ventilation off, a house will only cool very slowly even in the coldest weather. The ventilation system however, even with well-performing heat recovery, will cool the property if the lost heat is not replaced[23]. Thus, if the occupants are out during the day, and the heating system is 'timed-off' or the thermostat has been turned down, a Passivhaus can lose a few degrees of heat[24]. Of course, if the household chooses to open windows, then heat loss can be faster.

Turning the thermostat up above 20 °C will increase heat demand and gas consumption. Some properties have been logged as being warmer – this may be a thermostat adjustment, or may be the result of high heat gains from other activities, either way this can be household choice.

2014 was the warmest year on record in the UK, and included above average temperatures in the winter months; this will have reduced heating demand (the analyses have not been adjusted in any way for the weather).

Previous analyses (during the Innovate UK study) have confirmed that these considerations apply at Wimbish; but it is outside the scope of this quick assessment to consider these again. Readers of this paper should, however, bear them in mind.

[22] Note that more recent guidance on Passivhaus design (PHPP v8) gives greater emphasis to ensuring performance at the expected level of occupation – which in the UK is likely to be higher than PHPP estimates. Changes in PHPP v9 introduce a more realistic estimate of expected occupation levels – though these may remain unrealistic for UK social housing.

[23] If air quality is not a consideration, as it is unlikely to be when the occupants are not present, then losses can be reduced by turning the ventilation down to a minimum.

[24] It is important not to lose too much, since the heating system is not sized to heat the property rapidly.

B. Technical Appendix

This appendix explores some of the issues in more technical detail; it is aimed at Passivhaus Designers and other interested parties.

Some content is repeated from earlier in this document, to save having to look back.

Monitoring gas consumption

Although our monitoring equipment provides a large quantity of valuable data, it has unfortunately not proved adequate to separate the space heating demand from that for hot water, or to differentiate the supply from the boiler from that from the solar panel, with sufficient accuracy to be meaningful.

Thus we compare the expected gas consumption in each property (using figures from the Passivhaus Planning Package – PHPP2007 Boiler worksheet) with the actual consumption.

If a property uses what we consider to be an excess of gas (though their bills will remain small) it does not automatically mean that the fabric is deficient. It could be that the household likes lots of baths, or that the solar panel has a fault. Looking at the data in conjunction with water usage, and across the seasons, can help in understanding why a property uses excess gas.

Seasonal gas consumption

The space heating in a Passivhaus is only required in the coldest months, and demand diminishes rapidly as the weather warms. Hot water demand is fairly constant throughout the year. The grey bars in Figure 17 are the sum of these demands for a 3-bedroom house.

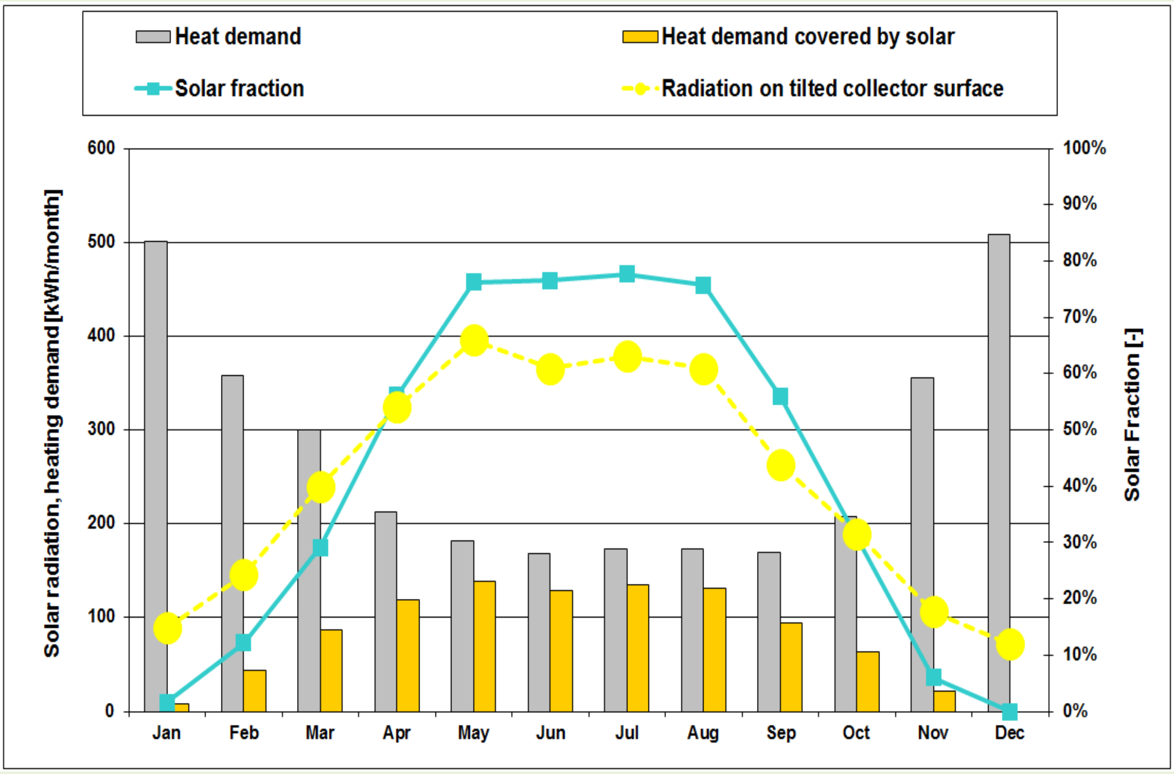

Figure 17: Heat Demand and Solar Contribution (PHPP as designed – but re-implemented in PHPP8.5)

The solar panels were sized to meet the summer demand, though since they were standardised across the 14 properties they fall a little short of meeting the demand for the larger houses (this figure is for a 3-bed house). The boiler is required to make up the difference between demand and the solar contribution, thus while some properties were expected to make no calls on the boiler during the summer, others might require some gas.

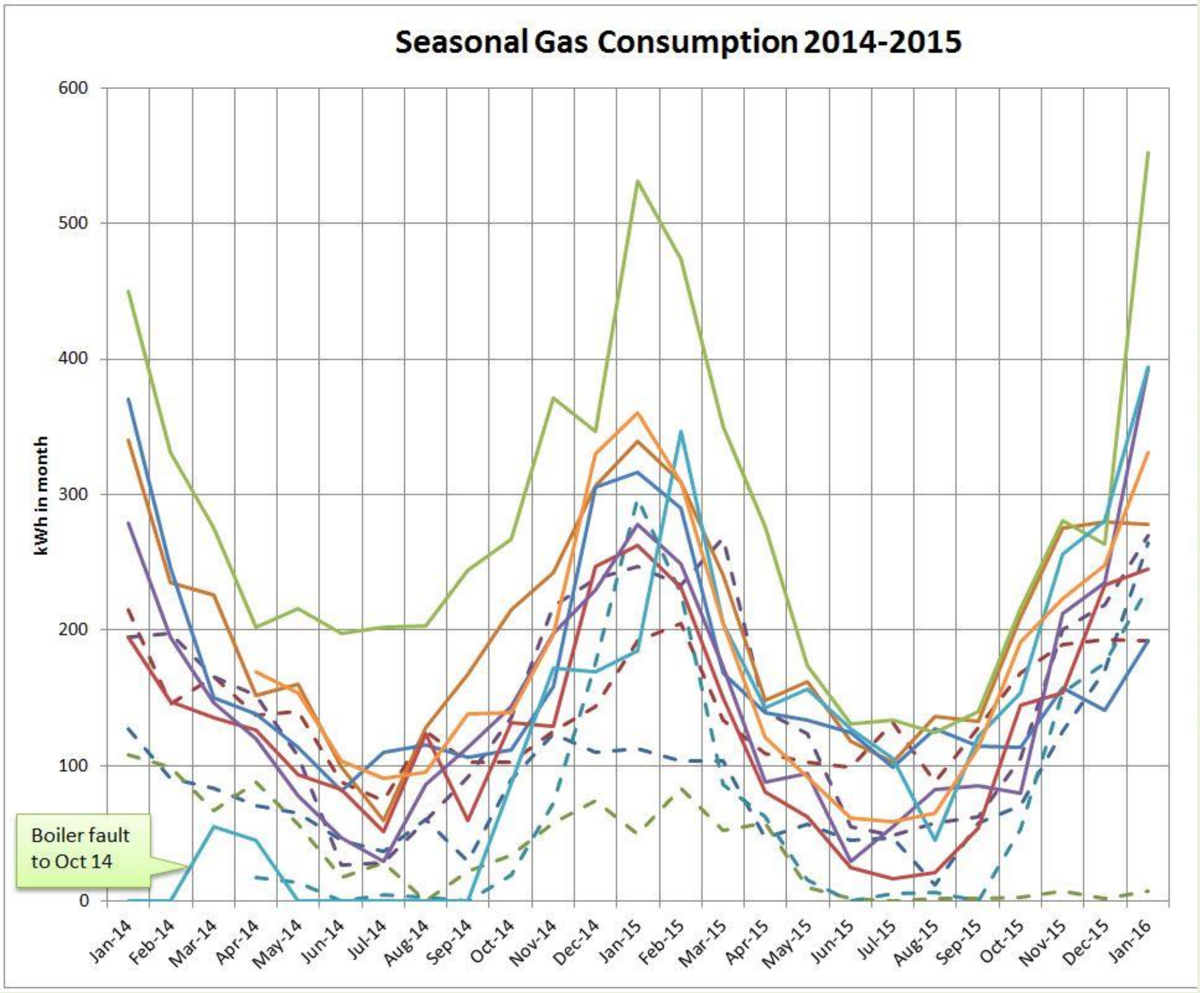

Figure 18: Logged Monthly Gas Consumption[25]

Figure 18 shows the logged monthly gas consumption and that some used rather more than predicted during the summers. This unexpected gas use may be down to one or more of the following:

1. Unanticipated use of space heating[26] – though the mild weather in 2014 makes this highly unlikely, and in any event the quantities would be very small
2. Reduced, or no, contribution from the solar panels. This could be because the panels are faulty, or because the settings are such that the boiler heats the water before the solar gets a chance, reducing the contribution it can make. Site visits to review the provision of hot water

25 Gas metering for 2 plots has not functioned; and in two others the metering was repaired at the end of March.

26 The Innovate UK Study detected some unnecessary summer heating – this might have been caused by leaving the thermostat by an open window.

were made autumn 2014. Comparing the April to September totals for the two years, three of the 2-bed houses each reduced their consumption by more than 240 kWh of gas[27].

3. Household sizes are larger, and/or the residents bathe more[28], than the assumptions in PHPP.

If we ask PHPP to recalculate assuming 5 people[29] living in the house, and to use its calculated internal heat gain, then we see significant changes in the heat demand (Figure 19). Hot water demand has roughly doubled across the year; space heating demand has fallen, because there are more gains from appliance use and from heat losses from pipework. The boiler will be needed to do more work across the year.

Actually, Figure 18 does not record as much extra summer gas use in the 3-bed house as this recalculation would imply, and the highest consuming property is a 2-bed house. There is evidently more going on that relates to household habits, and perhaps to the settings of the boiler and solar system, than we have been able to account for in this brief assessment.

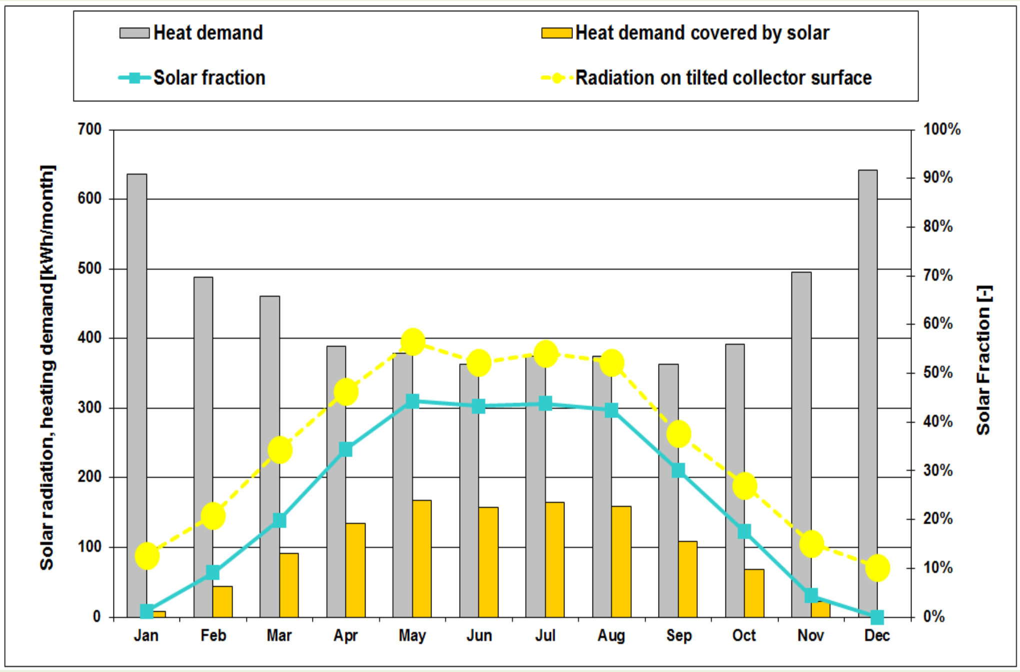

Figure 19: Figure 17 recalculated for 5 people and their internal heat gains

A recommendation from this is for future design to consider the impact on systems and their performance if occupancy levels differ from the Passivhaus norms. At Wimbish it would probably have been desirable to have larger solar panels on the houses. In addition, greater attention to the programming of the hot water supply system, and its explanation to the households, would have been beneficial.

27 While this is a significant percentage of annual consumption (nearly 10% in one case), and brings the properties closer to the expected design performance, it should be noted that it is less than £15-worth of gas at Equigas rates, and it is difficult to justify investigation of any other causes of the divergence.

28 In the Innovate UK study however, a questionnaire on bathing habits, and assessment against water consumption, failed to detect any significant increase in bathing.

29 Actually 2 adults and 4 small children

Expected Electricity Consumption

The Passivhaus standard does not include an explicit target for electricity use, although it must be accommodated within the total primary energy consumption of less than 120 kWh/(m^2·a). Since we know the expected gas demand, we can establish an allowed figure for electricity for each property – about 27 kWh/(m^2·a) for the houses and 31 kWh/(m^2·a) for the flats.

By comparison, if we divide the Ofgem medium typical domestic consumption value by the average national property size we get a rather higher figure of about 40 kWh/(m^2·a). Passivhaus are thus expected to consume only about ¾ of the electricity of a typical house. Having said this, any new house might be expected to have more efficient lighting and appliances and thus consume less than a typical (existing) house.

In general, the household electricity consumption at Wimbish may be described as 'normal', and not the reduced level hoped for in a Passivhaus. There are thought to be a number of possible reasons for this:

- Most households brought their existing, relatively inefficient, appliances with them; and where new appliances were purchased the capital cost was a higher priority than efficient use.
- Above average occupation levels leads to higher use
- Because gas bills are so much diminished, the combined utility bill will be well below household's expectations, meaning that the households pay less attention to their usage and cost of electricity
- In most UK households, there is a lack of connection (in the household's minds) between behaviour and the resultant impact on bills. For example a household (not at Wimbish) that complains about the cost of having to feed their electricity meter, yet persists in having several large screen plasma TVs and computers on all day.

High electricity use is not just a financial issue, in the summer the heat given off by these appliances can exacerbate the risk of overheating.

Ideally, a Passivhaus developer would provide energy efficient appliances; failing that a scheme to enable households to purchase such appliances without having to bear the sometimes higher up-front cost would be beneficial. Designs might also seek to encourage energy saving behaviours, for example by providing a drying cupboard rather than space for a tumble dryer. Handover to the residents should also include tips on reducing their electricity bills.

Thermal comfort in winter

The requirement in winter is to avoid low temperatures that may lead to discomfort and health issues such as hypothermia.

While a Passivhaus should be designed to be capable of maintaining a constant temperature of 20 °C, in practice the occupants may be happy to let the temperature fall some of the time, for example when they are out, or asleep. Conversely some households may choose a warmer temperature. When considering thermal performance, averages are often quoted, but they can hide extremes[30] – plotting the cumulative distribution for a period, in the case of Figure 20 for February 2014, 2015 and 2016, provides more detail:

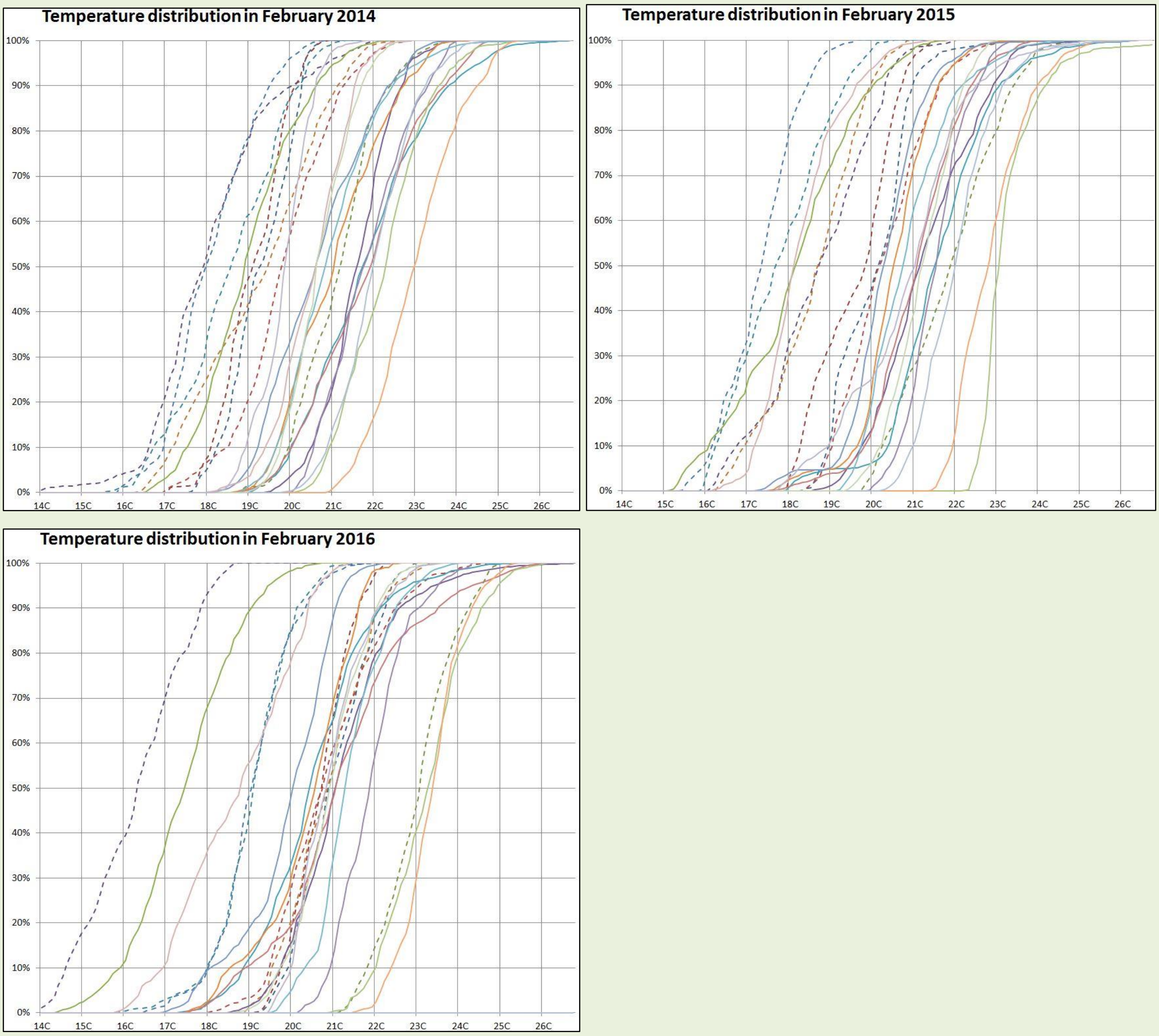

Figure 20: Winter Temperatures (flats dashed lines, houses solid)

30 Very cold half the time, and very hot the other half, will give an average 'good'.

Observations:

- Some of sensors logged temperatures above the 20 °C 'target' all of the time, and others only got there a small percentage of the month.
- The great majority of the readings are in the range 17 to 24 °C – showing that the properties remained warm and comfortable
- The calibration of the sensors has been found to drift, and some might be reading a degree or so out. [and a couple are believed to give inaccurate values some of the time] – the low figures from two sensors in Feb 2016 are suspect.
- Temperatures higher or lower than the 'target', may be occupant preference in adjusting their thermostat
- High temperatures might be the result of high levels of occupation and/or appliance use rather than turning the thermostat up.
- Looking at the 50% at 20 °C point for 2014 it is interesting to note that of those sensors generally cooler, all but one is in a flat, and only one of those warmer is a flat[31]. That the flats are cooler than the houses is thought to relate to the level and hours of occupancy rather than any inherent difference in the structure.

Overall the temperatures in February are excellent, though it should be noted that these were relatively mild Februarys[32].

Thermal comfort in summer

In summer the requirement is to keep temperatures down, to avoid the household suffering thermal stress.

There is concern[33] that new, thermally efficient, homes can overheat when it is difficult to dissipate excess heat.

The aim of Passivhaus design is to minimise this risk, with a metric of ensuring that 25 °C is not exceeded more than 10% of the (annual) occupied hours.

The Wimbish design met this criterion using the Passivhaus Planning Package (PHPP2007) current at the time; however migrating the model to a more recent version[34] suggests that a little less glazing or more shading may have been desirable in order to meet the criterion.

Our Innovate UK study analyses found:

- In practice, the 10% threshold had been exceeded by a significant margin in some of the properties.
- However, even in heat waves, the interior temperatures had not exceeded 30 °C, suggesting that in the hottest weather the dwelling's insulation has a beneficial effect.
- Occupant behaviour can have a large impact on the internal temperature during hot weather. Mediterranean practices of battening down the hatches during the day to avoid heat ingress,

31 The picture looks similar for 2015, but is a bit less obvious in 2016. There is a suggestion that households are a little warmer on average.

32 Though other than in extremely cold weather a Passivhaus ought never to struggle to keep warm.

33 For example by the Zero Carbon Hub, see http://www.zerocarbonhub.org/current-projects/tackling-overheating-buildings.

34 PHPP v8.5 has improved algorithms for the overheating calculation.

and throwing open windows when it is cooler at night, can avoid excesses. Avoiding heat generating activities such as using a tumble dryer, or a large plasma TV, helps too.

- Household opinions on their summer comfort varied widely, and seemed to relate to whether or not they perceived that they knew what to do to keep cool (rather more than actually how hot their homes were)

Although the 5 years of occupation have been warm years overall, they have not had an extended period of hot days that would thoroughly test the dwellings and their occupants, thus although they provide a good test of over-heating in general, they have not provided a thorough test of what might happen in an extended heat wave.

Figure 21 shows the cumulative distribution of values logged by each sensor for the whole of 2014 and 2015 (ignoring sensors that malfunctioned part of the time[35]).

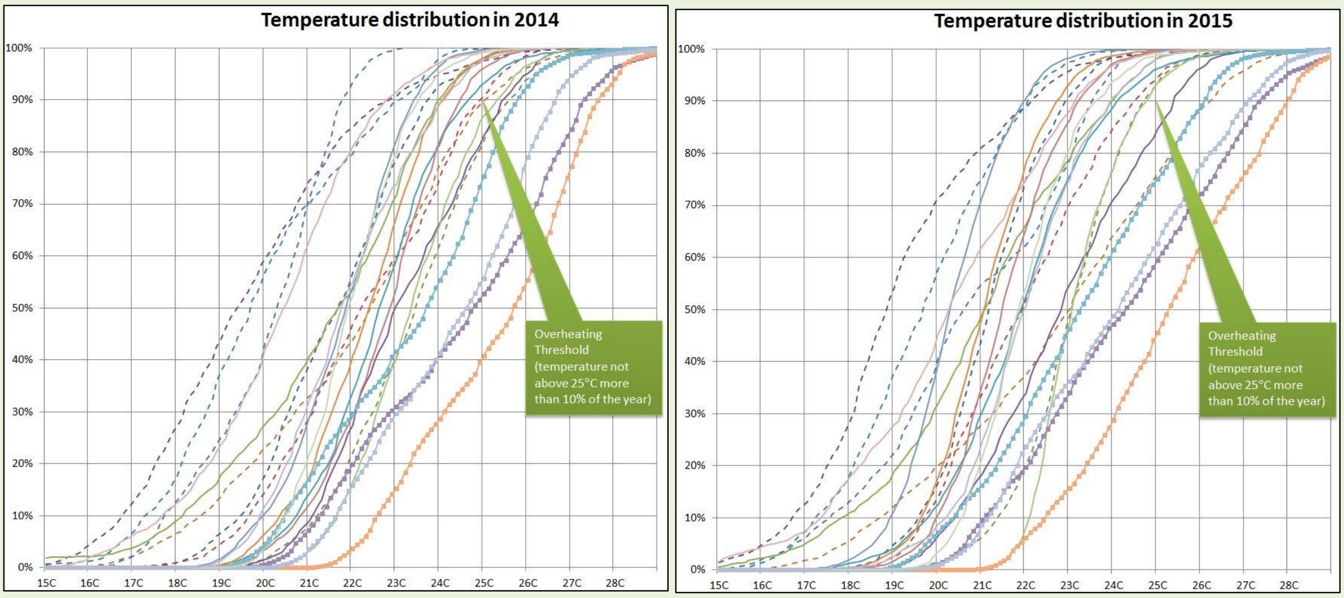

Figure 21: 2014 and 2015 Temperature Distributions (flats dashed lines, houses solid – sensors with markers in the 3-bed house)

The four warmest rooms are all in one 3-bed house[36], with the kitchen the warmest, being over 25 °C 59% of 2014. There are considered to be a number of reasons for the warmth in this house:

- The household says that they like it
- The property has the highest occupation of all the properties
- They have joint highest electricity consumption
- They are reluctant to open windows in summer, having young children
- The kitchen is south-facing and the full width of the house, catching maximum solar gain, though shaded by the Brise Soleil

Three other rooms monitored fail the criterion in 2014 as well, but by a lesser degree. Two of these are in two-bedroom houses, where the sole sensor is in the lounge. While it is possible that the

35 Low readings recorded by other sensors are also suspect; though some low readings are known to be behavioural.

36 The tenancy is scheduled to change hands summer 2016, and it will be interesting to see the impact.

kitchens are warmer (both rooms are south-facing), generally the effect of the MVHR is to even temperatures around the properties at any one time.

The warmest month of the year tends to be July, and Figure 22 shows the distribution of readings for the month.

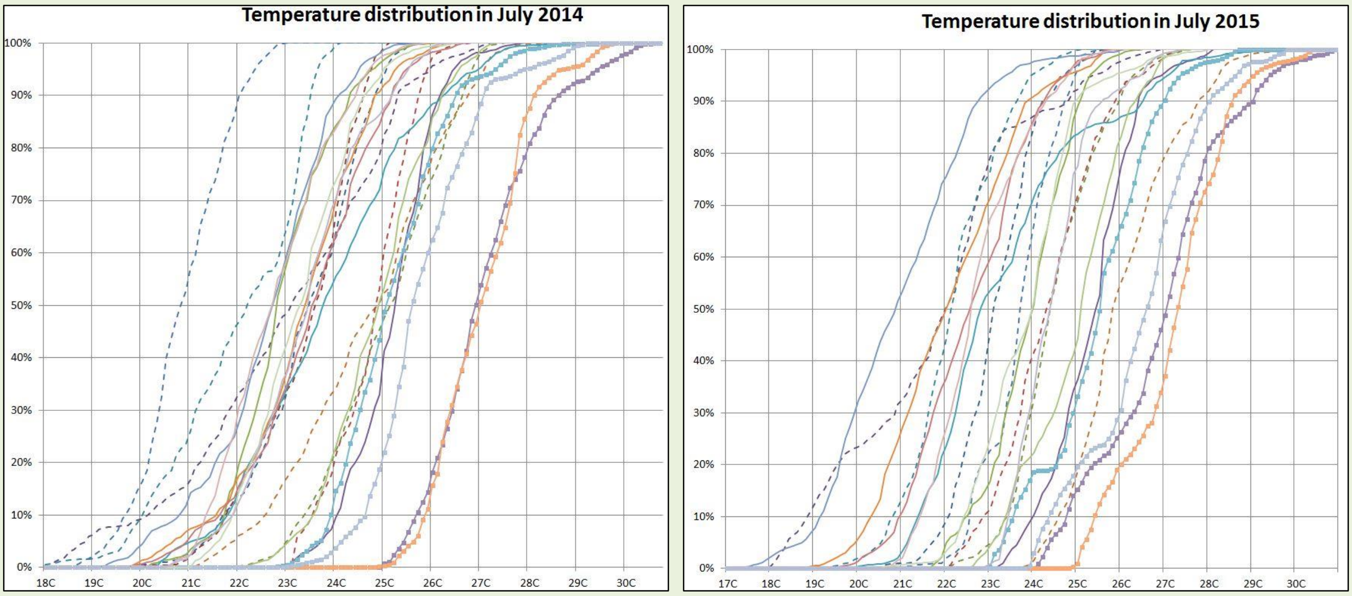

Figure 22: Summer Temperature Distributions – July 2014 and 2015

The hottest sets of readings are again from the 3-bed house that has high occupation, where the kitchen and the bedroom were above 25 °C virtually all month. (The distribution curves of 4 sensors in this house are highlighted with markers)

Some of the sensors did record consistently lower temperatures. Again the flats are generally cooler than the houses; lower occupancy is likely to be a factor, along with the greater thermal mass in the flats.

The large variation in temperature between the properties is puzzling[37]. That some remain relatively cool implies that it can be done.

[37] Some sensors have been found to give inaccurate readings some of the time, and generally the calibration may have drifted. Before any strong conclusions were drawn from this data the sensors ought to be checked, and ideally be replaced.

Humidity

In a similar manner to temperature the relative humidity should be neither too high nor too low.

The air flows required in a Passivhaus are designed to be sufficient to remove the risk of excess relative humidity (RH) and consequent condensation and mould; this is dependent on the MVHR system having been constructed, commissioned, maintained and operated correctly. Our Innovate UK study analysis found that, following an initial drying-out period when there was high humidity, values have stayed well below upper thresholds[38].

There is a tendency for mechanically ventilated properties to lose moisture during the winter. This is because an MVHR removes moisture from the property along with other pollutants (the outgoing air being warmer and having a higher moisture content than the replacement air), and unless this moisture is replaced by other means[39] the result will be a gradual reduction in the humidity level. There is a chance that a property will become overly dry by the end of the winter (for example below 20% RH), with risk of respiratory difficulties for the occupants.

In the summer, warmer outside air can hold more moisture, and thus internal RH levels in a mechanically ventilated property will be higher. In any case, windows are more likely to be open and the operation of the ventilation system will not have as significant an effect.

‘Drying out’ in winter is unlikely to be as much an issue in maritime southern England as it is in central Europe, where the winter air is colder and thus drier, but checks should still be made. Our Innovate UK study analysis found that there was a reduction in the humidity level through the winter, which recovered in the spring when windows were opened. The lowest values were not at risky levels, however the median levels in 2013 were a little lower than in 2012 (falling to approximately 35% from 40%) and there was a question whether continued drying out of the fabric of the buildings might result in even lower values in 2014 and subsequent years.

A technical solution to this risk is to replace the standard heat exchanger in the MVHR unit with one that also recovers humidity. A trial in winter 2013/14 of such an enthalpy exchanger has been conducted in the two houses (2-bed and 3-bed) which have MVHR monitoring in place.

[38] Thresholds can be defined in various manners, but values consistently above 65% RH may cause issues.

[39] For example, evaporation from clothes drying, transpiration from plants, or moisture from cooking.

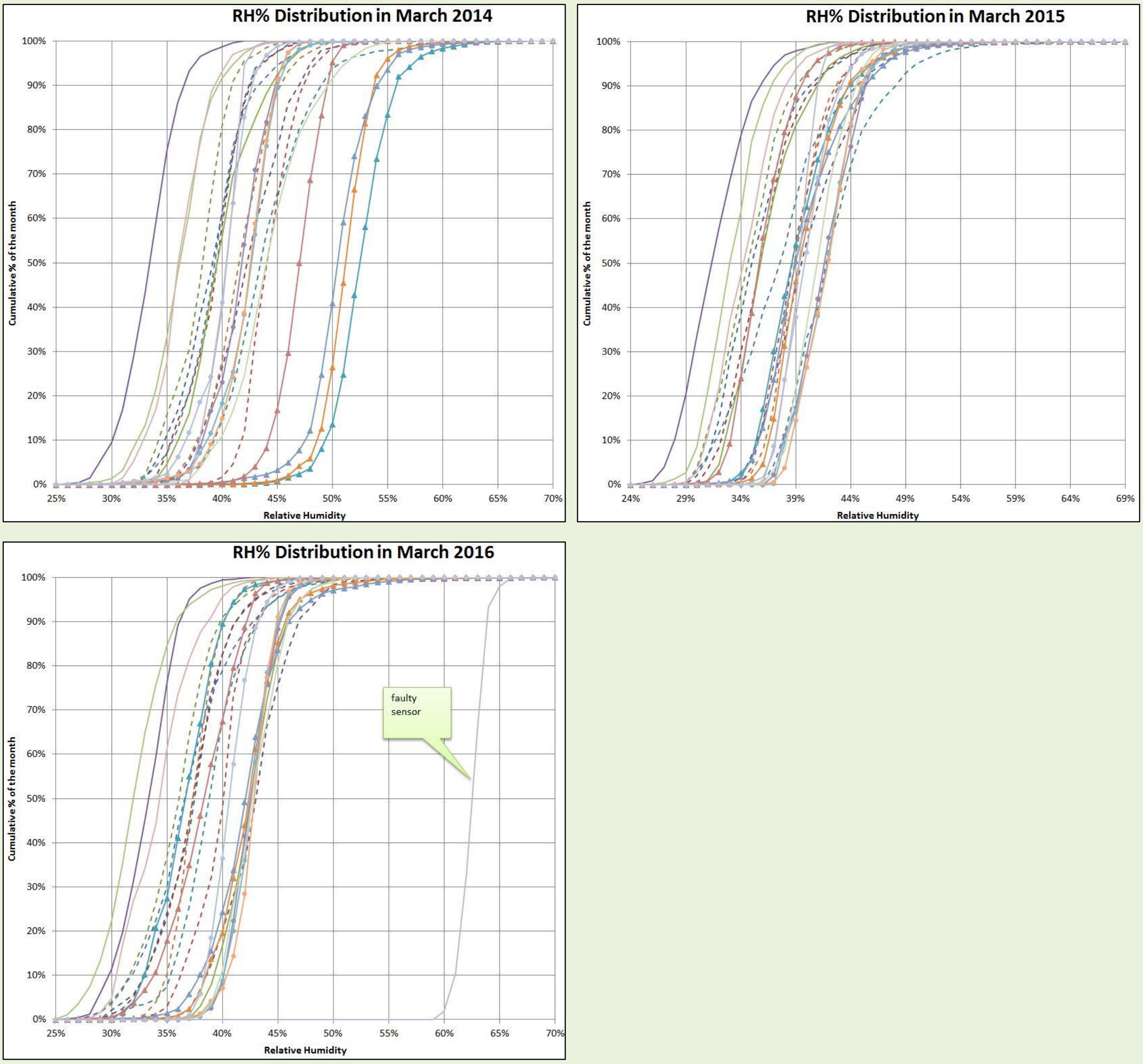

Figure 23: Humidity Distribution End Winter (flats dashed lines, houses solid – triangle markers in the fully monitored 2-bed house)

The charts for March in 2014-16 (Figure 23) show that for each sensor the values for 80% of the time were within a narrow band, though there are quite large differences between sensors. This is likely to be caused by variations in household practices that add moisture to the air.

The four sensors with the highest RH values in 2014 were all in the 2-bed house, with one of the enthalpy exchangers; the 3-bed house does not show the same increase. In subsequent years, after the trial, the values in the 2-bed house returned to being similar to the other properties.

Overall, the RH levels are perfectly acceptable. Very few readings are at the upper threshold, and few below 30%. No evidence has been found of a downward trend, and even the driest property only falls below 30% RH a small percentage of the time.

Ventilation

A Passivhaus is designed to not only be thermally efficient, but also to be air-tight[40]. Minimising leaks through the fabric avoids heat loss, and reduces the risk of moisture in air leaking from the building condensing and damaging the fabric.

Having largely eliminated draughty leaks, one must then add assured ventilation to remove pollutants, including excess moisture, for the benefit of the occupants, and of the fabric. For this to be assured in a domestic environment this ventilation should be mechanically driven, that is by fans. These may run continuously, or be demand driven (by sensors, or perhaps, albeit with risk, by the occupants). Mechanical ventilation systems can be centralised, or be distributed through the buildings.

Much of the time a simple extract system might suffice, but in winter it is wasteful to lose all the heat in the exhaust air, and a heat recovery unit helps the dwelling be energy efficient. Thus UK Passivhaus, Wimbish included, are generally fitted with a mechanical ventilation system with heat recovery, or MVHR. The MVHR is the essential heart of the Passivhaus – without it functioning effectively the building would suffer from poor air quality, high humidity and probably condensation.

For an effective system the design, procurement, installation, commissioning, maintenance and operation must all be done well.

A confidential technical annex to the Innovate UK Wimbish Study report commented on each of the above aspects. Although the air quality (see section 5) and other factors have remained good the procurement and installation were not quite as good as they could have been. The result being that the commissioner had to set the fans at higher setting than expected in order to overcome the pressure losses and deliver the designed air flows; he also found it difficult to balance the systems in a couple of the dwellings, and in one house there was a larger than desirable difference between the sum of the extract flows and the exhaust – implying that air was being drawn through a leak.

The maintenance is largely the timely replacement of filters. Hastoe have been carrying this out for the tenanted properties, with shared owners being responsible in their homes. Since the cost of this is about £50 for a set of filters it should only be done when necessary; however, other than in the three properties where monitoring records the electricity use by the fans the need is not obvious until it becomes a serious need. Monitoring shows when energy use is rising (the fans needing to work harder to maintain air flows when the filters become blocked) – see section 6; it might help for daily figures to be visible to the householder, or for the unit to raise an alarm when a preset threshold was reached. Hastoe's service arrangement works on a twice-a-year basis; while this should be about right for the houses, the lower flow rates in the flats mean that it could probably be less frequent there. A 'serious need' is indicated by increasing noise from the unit as the fans complain that they cannot maintain the air flows. If the air flows are compromised then so will be the air quality in the dwellings, and it could prove difficult to deliver sufficient heat via the air supply.

The routine servicing is dependent on being able to find a mutually convenient time for the householder to grant access to the service engineer. On occasions this has led to a delay of a few weeks, and the monitoring has observed a modest reduction in air quality.

Innovate UK have published a Meta Study of the MVHR systems used in the BPE programme, available from http://www.fourwalls-uk.com/mvhr-meta-study/. This includes a Wimbish Case Study compiled from extracts of the Wimbish study report (confidential technical annexes) to Innovate UK. The case study is rather oddly titled '*Impact of inadequate maintenance*', presumably because it includes mention of the deterioration of air quality in the rare event of a delayed filter change.

Figure 6.3h in the meta-study, which was copied from our report, shows a cost-benefit analysis for use of an MVHR. Actually we think that such analysis is specious. One should not really countenance an energy efficient building in the UK without assured ventilation, best delivered at present by an MVHR;

[40] Tested to be less leaky than 0.6 air changes per hour at 50 pascals.

as such the MVHR system enables the building, and cannot be justified stand-alone by a cost-benefit analysis. The figure was included in our report as an illustration that if one really did want to think about the numbers then this is what they might look like. The key clause is

> *"we must bear in mind that the quantity of heat required has been hugely reduced by the Passivhaus, for which we need ventilation. Having saved several hundred pounds a year on heating, we should not quibble over spending a small portion of this on providing fresh, healthy air."*

With one exception, the households have largely used the MVHR as the design intended, and as explained during the extended handover process. Some found the controls over-complex, and simply left the system on the default setting of speed 2 – which has worked fine. Others have been more savvy and used the boost to remove cooking smells or moisture from bathing, and a low setting when away on holiday. The exception is a flat where the tenant was adamant that he would prefer to have the MVHR off and leave windows ajar. This has generally been the coolest flat, yet his gas bills are comparable with others; the property is not one of those monitored in detail, so we are unable to comment on the impact on air quality, though it is unlikely to be good. If he wished to be warmer he would probably have to use an electric heater as most heat is designed to be delivered by the air supply, this would raise his bills significantly – the lesson is to use the MVHR!

In conclusion, the MVHR systems are doing what is expected of them, though with a bit more energy cost than expected, and with care required to keep the filters clean.

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