GHA Monitoring Programme 2011-13: Technical Report

Derwenthorpe prototypes

Results from Phase 2: Post-occupation testing of sustainable new homes

Acknowledgements

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Front cover image: Derwenthorpe prototypes (Temple Avenue) (image Richards Partington Architects)

Good Homes Alliance Monitoring Programme 2011-13:

Technical report: Derwenthorpe prototypes

Results from Phase 2: Post-Occupation Evaluation

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1 Introduction

The Good Homes Alliance Monitoring Programme aims to measure and monitor the performance of high-level sustainable, new build homes. The programme consists of the following research phases:

1. *Post-construction testing:* testing the thermal efficiency of the building shell
2. *Monitoring in Use*: analysis of in-use data about energy and water consumption, and temperature and Internal Air Quality (IAQ) conditions.
3. *Post-occupation evaluation (POE):* analysis of resident and user behaviour patterns, comfort and satisfaction levels and perceptions.

This document reports on the results of the post-occupation evaluation carried out at two prototype dwellings (referred to as Houses A and B in this study) at Temple Avenue, part of the Derwenthorpe development, located approximately 2.5km to the east of York. The in-use monitoring was undertaken by the Centre for the Built Environment (CeBE), Leeds Metropolitan University and follows research by the group investigating the design and construction of the building and services, as reported in Miles-Shenton et al. (2011) and Joseph Rowntree Housing Trust (2012).

House A was used primarily as a show home for the adjacent development and on a number of occasions for meetings organised by JRHT. House B was occupied by a family throughout the monitoring programme. While of similar size and layout, the houses were built using different construction methods.

Monitoring equipment was installed in the dwelling between December 2011 and May 2012. Sensors measuring temperature, relative humidity and carbon dioxide were installed to monitor the internal environmental conditions. Energy meters were installed on each ring main, at the fuse box; this enabled the demands for electricity to be described by its end use (e.g. lighting, cooking, and appliances).

Heat meters were used to determine heat supplied by the boiler to hot water and space heating. Cold water flow meters were also installed to measure cold water usage and determine the volume of hot water used within the dwelling (this was achieved by measuring the amount of cold water supplied to the combination boiler). The electrical power output from the roof-mounted photovoltaic slates were monitored both before (DC) and after the inverter (AC) to measure its efficiency. An external weather station was also installed to measure external climatic conditions, which included air temperature, relative humidity, rainfall, wind speed and solar insolation.

Occupant surveys and interviews were not successful in this study. At House A, although unoccupied, the BUS questionnaire was issued to a number of the individuals who participated in meetings undertaken within the dwelling. At the time of writing, none of these questionnaires have been returned. Further, the BUS questionnaire was posted to the householder of House B with a stamp, addressed envelope for return to the research group, on 13th July 2012. The questionnaire had not been returned at the time of writing either.

1.1 The Development

The two dwellings are 2.5 storey, three bedroom detached houses built on behalf of the Joseph Rowntree Housing Trust (JRHT). The dwellings were constructed between July and December 2009 as prototypes prior to a larger 400 dwelling development at Derwenthorpe. The larger development will have an Energy Centre and an on-site central biomass heating system. A car share scheme has been proposed and information sharing measures are also hoped to have an impact on people’s carbon footprint (JRHT, 2012).

Figure 1. Derwenthorpe prototypes, Temple Avenue

The dwellings were designed so that high levels of fabric performance would be achieved. Airtight construction was coupled with a whole-house MVHR system, high levels of insulation were installed and measures were undertaken during the design and construction process to minimise the amount of thermal bridging.

Some electrical power is supplied to the dwellings by roof-mounted PV tiles and the house can, in the future, be connected to the district heating system that will form part of the larger development. In order to minimise energy demand, the electrical appliances installed within the dwellings are A- rated (washing machine, dishwasher and fridge-freezer), and the light fittings are suitable for high energy efficiency bulbs.

Additional environmental measures include rain water harvesting and low flush toilets. Each dwelling is designed to be a lifetime home; this has led to the dwelling being capable of being adapted to meet people's needs throughout their lifetime. House B has a disability lift/ platform fitted.

Based on the performance of buildings at design stage, the dwellings are expected to have a Dwelling Emission Rate of 12.35 and 12.39 $kgCO_2/m^2/yr$, for dwellings A and B respectively, and achieve an overall SAP rating of B. They are also designed to meet Level 4 of the Code for Sustainable Homes.

2 Building Construction

2.1 Building fabric

House A was constructed using a structural insulated panel (SIPs) build system that was clad externally in brick. The external walls are dry-lined internally with plasterboard on battens, creating an internal service void between the timber-frame and the plasterboard.

House B was constructed using thin joint masonry cavity wall construction. The external walls were parged internally and then dry-lined with plasterboard on dabs.

Each dwelling was orientated North-West to South-East, with large glazed elements facing towards the South-East. Each dwelling has a sunspace designed to act as a thermal buffer in winter and to induce the stack effect in summer, to promote cooling. Ground floors are comprised of a suspended concrete slab with insulation placed below the slab, and the upper floors were constructed using timber I-beams. Roofs are a tiled pitched design and the windows are double glazed. Windows are double glazed argon filled units with one low-e coating and a warm edge spacer and the external doors are high performance units.

The as-built fabric performance of both dwellings was measured using the procedure described in the Leeds Met Coheating test protocol. A Coheating test was simultaneously undertaken on both dwellings between the 4th January 2010 and the 4th February 2010, with usable data being collected from 9th January 2010 onwards. The results of these tests are summarised in Table 1 below. In the case of House A, the SIPS prototype, the measured heat loss is 12.2% higher than the predicted value. In the case of House B, the thin joint masonry prototype, the measured heat loss coefficient is 15.1% higher than predicted. Further details of the test results can be found within (Miles-Shenton, Wingfield, Sutton & Bell, 2010) and the GHA Monitoring Programme 2009 – 2011: Technical Report.

Table 1. Comparison of Predicted and Measured Fabric Performance

	Dwelling A (GFA = 154.5 m^2)	*Dwelling B (GFA = 151.76 m^2)*
	Heat loss coefficient (W/K)	*Heat loss coefficient (W/K)*
Predicted	118.43	129.85
Measured	132.86	149.47

Variation	+ 14.43 (12.2%)	+ 19.62 (15.1%)

2.2 Building services

Although different construction methods were used to construct Houses A and B, in the main, the same mechanical and electrical services were installed within both dwellings. The only exceptions to this relate to a lift installed in House B for use by a disabled occupant and electrically-operated window opening mechanism for the 1st floor South-East facing bedroom windows in House A.

A summary of the main services installed within the dwellings is detailed below:

- Space heating is provided via a 24kW Worcester Bosch Greenstar 30Si wall-mounted gas-fired modulating condensing combination boiler with a fan-assisted flue which is located in the kitchen of each dwelling (see Figure 2). The boiler has a stated SEDBUK rating of 90.1% and has a frost thermostat (obtained from manufacturers literature). The boiler does not contain a modulating pump and no weather compensation is fitted. The boiler feeds a conventional wet central heating system and supplies all of the hot water to the dwellings. Control of the space and water heating system is provided via a 24 hour electronic programmer that is integrated within the boiler, and a room thermostat located in the hallway.
- Ventilation is provided via a 120W Vent-Axia Sentinel Kinetic B whole-house MVHR system which is located in the loft space of both dwellings (see Figure 3). The unit incorporates a summer bypass mode that is operated manually by accessing it via a menu system from the control panel on the front of the main unit. Boost operation in the kitchen is provided via a wireless remote control. There is no boost switch in the bathroom or en-suite.
- 14 Solarcentury C21e photovoltaic tiles are incorporated within the South-East facing roof of each dwelling (see Figure 4), the total area of each array is 5.2 m^2. Each tile is rated at 47Wp, giving a total of 0.658 kWp per dwelling.
- A rainwater harvesting system is also installed in each dwelling (see Figure 5). The rainwater storage tank is located in the back garden of each dwelling and feeds the WC

cisterns and an outside tap. When the amount of rainwater contained within the tank drops below a certain level, the tank is topped up with cold water from the mains. Dual flush WC's, low flow taps and a low flow thermostatic shower mixer have been installed to reduce water consumption.

- 75% of the internal lights to all habitable rooms have dedicated low energy fittings with a minimum efficacy of 40 lumens per Watt. External lights have a minimum efficacy of 40 lumens per Watt and the maximum wattage of the two installed security lights is 150 Watts. Both security lights have a PIR and daylight shutoff.
- An electric induction hob and oven are installed within each dwelling.
- An integrated fridge-freezer, dishwasher and washing machine has been installed in each dwelling with an A or A+ rating. Additionally, residents have been given information about the EU energy labelling scheme for domestic appliances and advice about the selection and operation of energy efficient appliances to encourage them to install AA+ appliances.

Figure 2. Worcester Bosch Greenstar 30Si combination boiler.

Figure 3. Vent-Axia Sentinel Kinetic B whole-house MVHR system

Figure 4. Solarcentury C21e photovoltaic tiles

Figure 5. Rainwater harvesting system.

2.2.1 Ventilation commissioning

Approved Document Part F (2006) ventilation requirements have been compared to grill-flow measurements undertaken by Leeds Metropolitan University. Measurements were undertaken on several occasions as a discrepancy was found between the measured airflow rates and those stated on the commissioning certificate, as well as airflow required by the specifier. Repeat airflow measurements were undertaken following visits by the contactor to bring the system to an acceptable standard. The airflow measurements stated for House A represent the system as finally commissioned, those stated for House B represent airflow measured following the penultimate visit by the contactor. Although no final airflow values are available for House B, JRHT assured the Leeds Metropolitan University research team that House B MVHR system was ultimately commissioned to a satisfactory standard.

As seen in Table 2, both dwellings extract rates largely fulfilled the requirements for extract ventilation listed in Approved Document Part F (2006), with the exception of the bathroom of House A which was 0.2l/s below requirement, and the kitchen of House A which was 0.1l/s below requirement. Supply ventilation for House A was ~2/3 what is required by Part F of the 2006 Building Regulations, potentially resulting in indoor air quality issues. House B flow rates are ¼ the requirement before final commissioning. Without following up the commissioning report this dwelling could have experienced severe indoor air quality issues.

Table 2. House A & B: Measured ventilation airflow rate compared to Approved Document Part F (2006) requirement

Room	*Part F requirement*	*House A measured airflow rate*	*House B measured airflow rate*
Kitchen	Extract 13 l/s	12.9 l/s	15.6 l/s
WC	Extract 6 l/s	9.9 l/s	11.3 l/s
Bathroom	Extract 8 l/s	7.8 l/s	8.1 l/s
En-Suite	Extract 8 l/s	8.4 l/s	9.6 l/s
Whole building	Supply 46 l/s (based on min. requirement 0.3l/s per m^2)	29 l/s	12 l/s

Supply and extract rates are reasonably well balanced in House A, this is illustrated in Table 3. The MVHR system in House B was highly unbalanced, without rectification this would have had reduced the energy efficiency of the system, in addition to reducing its effectiveness.

Table 3. House A & B: Part F requirement for balanced airflow rates

	Standard		*Boost*	
	Supply	*Extract*	*Supply*	*Extract*
House A	29 l/s	28.2 l/s	44.5 l/s	39 l/s
House B	12 l/s	30.3 l/s	15.8 l/s	44.6 l/s

2.3 Part L examination

Each dwellings' SAP assessment was undertaken using the SAP 2005 methodology. SAP 2005 worksheets predict values for the annual energy consumption of an occupied dwelling. It has not been possible to compare many aspects of each dwellings energy use as there is currently insufficient data to compare annual energy use with that in the worksheet. An attempt has been made to extrapolate data for PV energy generation and MVHR energy consumption from the data where appropriate; these values should be treated with caution.

Both dwellings MVHR electricity consumption is below the SAP 2005 worksheet assumption, seen in Table 4. There is only a 20kWh difference between the value based upon unoccupied (six month data) and occupied data (June 2012). There is a smaller discrepancy between SAP assumptions in House B and that extrapolated from the in-use data. It is interesting to note the difference in SAP 2005 assumption between dwellings of almost identical size and system provision.

Table 4. House A & B: Measured vs. SAP 2005 worksheet MVHR electricity requirement

	MVHR electricity requirement SAP 2005 prediction	*MVHR electricity consumption Measured*
House A	450 kWh/year	254 kWh/year (based on six month data)
		274 kWh/year (based on June 2012 data)
House B	394 kWh/year	248 kWh/year (based on six month data)
		316 kWh/year (based on June 2012 data)

It can be seen in Table 5 that the SAP 2005 prediction for PV generation is extremely close to that which has been extrapolated from the data; this is unsurprising given that the array efficiency is close to its design value. Also noteworthy is the discrepancy between the generation value stated in the SAP 2005 worksheet and the one ascertained using the methodology and system details.

Table 5. House A & B: PV generation comparison to SAP 2005 worksheet

	PV generation (SAP 2005 worksheet)	*PV generation (using SAP 2005 methodology)*	*PV generation (based on six month data)*
House A	565 kWh/year	548 kWh/year	572 kWh
House B	565 kWh/year	548 kWh/year	Insufficient data

3 In-use Monitoring Results

This section outlines the results of the intensive monitoring undertaken at the properties. House A remained largely unoccupied from completion until temporary occupation during June 2012. The dwelling acted as a show home for the adjacent development and on occasions for meetings organised by JRHT, so was only occupied occasionally. The heating system was operational in House A from 11th January 2012 onwards; therefore the energy consumption of the dwelling is considerably lower before this date. Changes were also made to the space heating thermostat setpoint during the monitoring period, usually during the intermittent occupancy. However, it is not known what these changes were. Presented in this section is 6 months of monitoring data from the empty dwelling. This data provides a case study of the baseload requirements of an empty dwelling. Data between December 2011 and May 2012 (inclusive) have been presented as this proved to be the most comprehensive.

Obtaining in-use monitoring data for House B proved to be considerably more problematic. Issues included occupants unplugging the data logger and the CO_2 sensors, as well as equipment failure; notably the heat meters measuring boiler output and the DC kWh pulse meter connected to the PV system. This has resulted in sporadic and inconsistent energy use data gathered between December 2011 and May 2012. It has only been possible to extrapolate complete and reliable in-use monitoring energy data from June 2012 onwards. The monitoring period reported here for House B is from October 2012 to March 2013, thus incorporating most of a heating season.

3.1 Total energy consumption

3.1.1 House A

Table 6. House A: Monthly total energy consumption per floor area

Month	*Total energy consumption per floor area (kWh/m^2)*
December 2011	0.5
January 2012	7.6

February 2012	9.4
March 2012	4.6
April 2012	5.4
May 2012	2.5

The variation in gas consumption observed in Figure 6 was a result of the central heating system operating from 11th January 2012, responding to heating demand. The thermostatically controlled hydronic central heating system operated on a timer controlled 18 hour daily cycle (~ 05:00 – 23:00).

Electricity consumption from mains supply and photovoltaic production is low. This is expected because the unoccupied dwelling has only a small number of systems and appliances running.

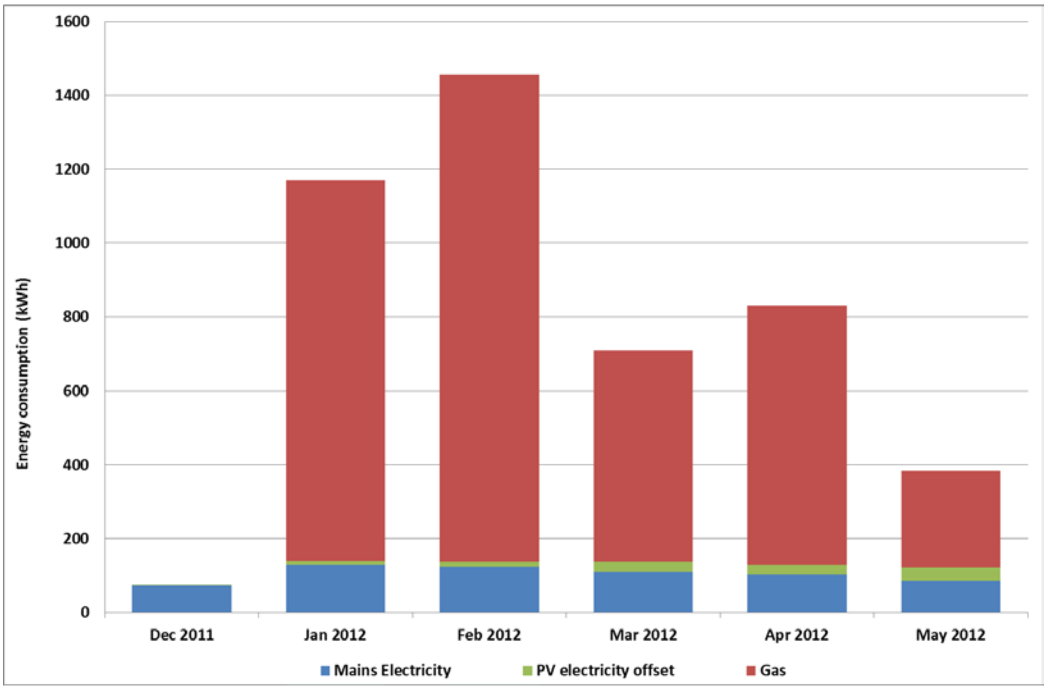


Figure 6. House A: Monthly energy consumption by energy source

3.1.2 House B

Table 7. House B: Monthly total energy consumption per floor area

Month	*Total energy consumption per floor area (kWh/m^2)*

October 2012	14.1
November2012	13.8
December 2012	17.7
January 2013	16.9
February 2013	15.4
March 2013	16.8

Figure 7 shows mains electricity consumption and gas consumption, but not PV electricity generated and used within the dwelling. This is because, unfortunately, the data from the import/export meter was unreliable, and hence the PV offset calculation was also unreliable. However, the generated PV electricity can be seen in Figure 23. This shows that the amount generated was very small compared with the total electricity consumption, except during March 2013 when the equivalent of around 13% of total electricity consumption was generated (though not necessarily used within the dwelling).

Gas consumption was lowest in October, and remained relatively high from December through to March. In contrast electricity consumption was highest in October, mainly due to a high level of appliance consumption.

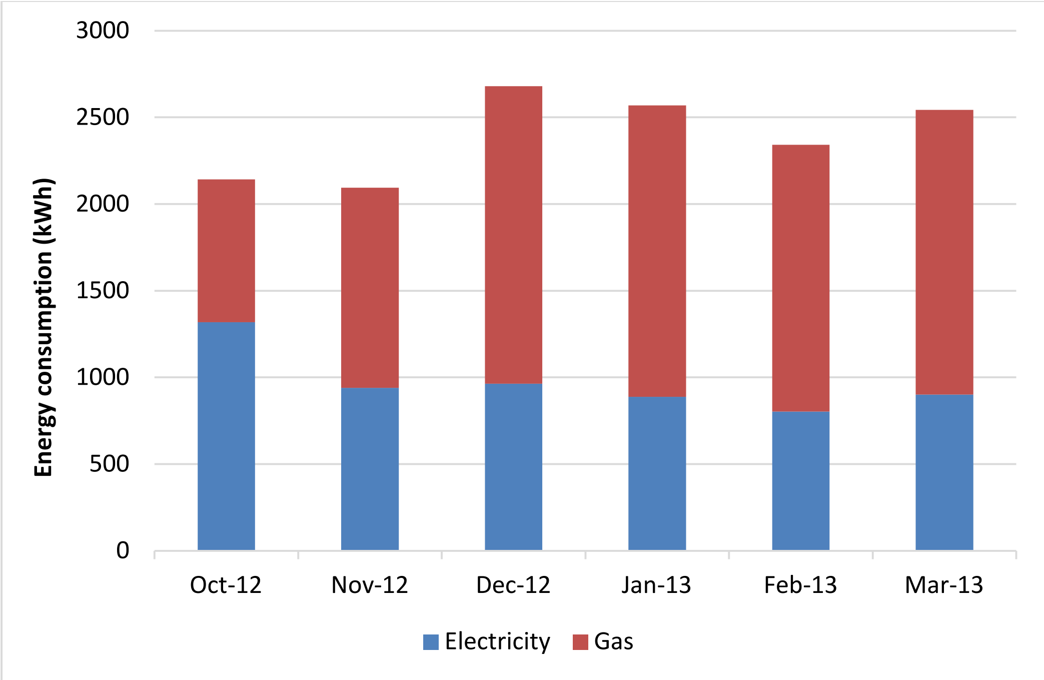


Figure 7. House B: Monthly energy consumption by energy source, excluding PV

3.2 Total energy by end use

3.2.1 House A

Winter (Dec-Feb) and spring (Mar-May) energy consumption was predominantly apportioned to space heating purposes, illustrated in Figure 8 and Figure 9. The reduction in heating demand in spring results in electrical end uses increasing their proportion of consumption within the dwelling. End uses associated with space heating also include the energy required for boiler control and operation and pump operation, as well as boiler inefficiency. Boiler inefficiency is calculated by subtracting the total boiler energy output for heating and hot water from the energy supplied to the boiler.

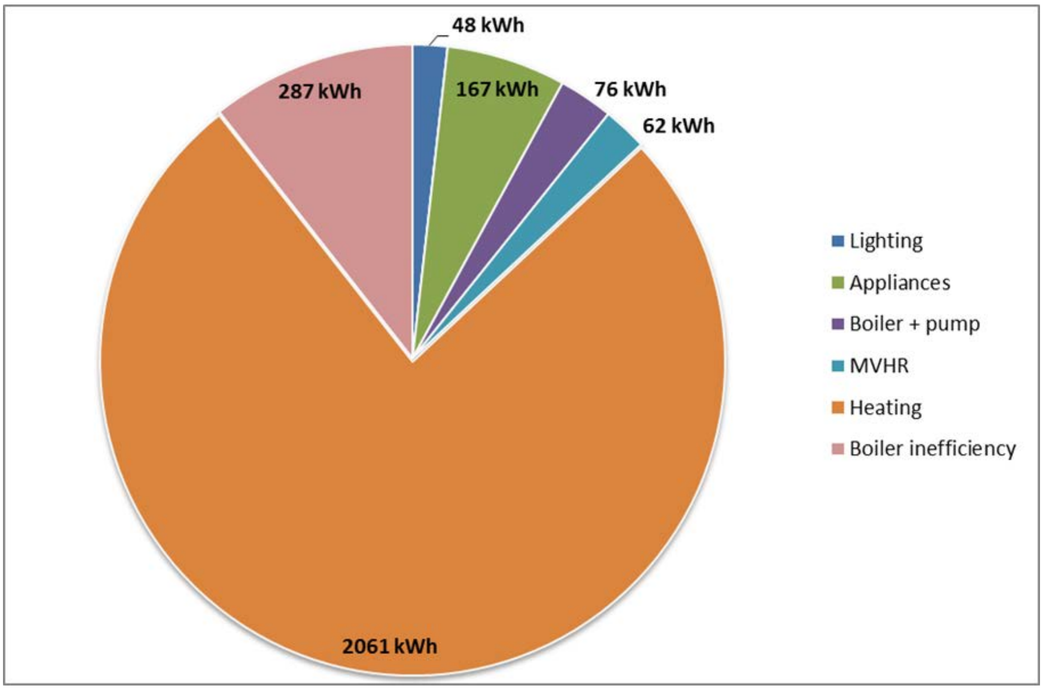


Figure 8. House A: Winter 2011/12 energy consumption by end use

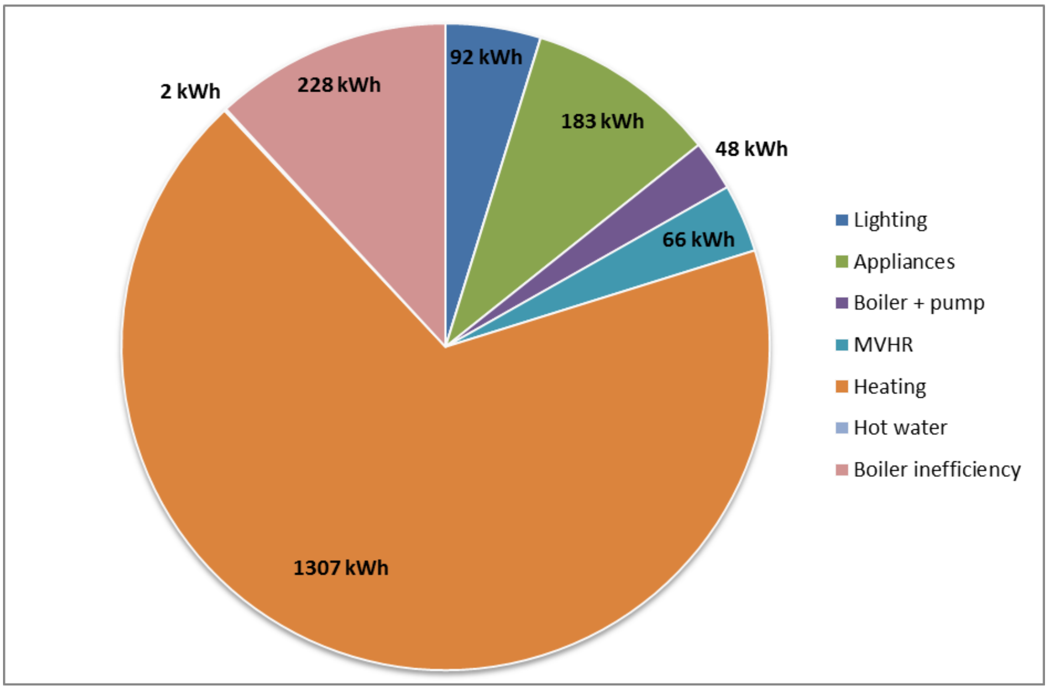


Figure 9. House A: Spring 2012 energy consumption by end use

Consumption in House A was primarily related to space heating, therefore energy consumption was highly dependent on the external temperature. The relationship between heating energy consumption and external temperature was inversely proportional, as illustrated in Figure 10. Energy consumption associated with the boiler (operation and inefficiency) and central heating pump was proportional to heating system consumption.

There was no energy consumption attributable to hot water during winter; spring hot water energy consumption is only 2 kWh and inconsequential in terms of overall energy consumption.

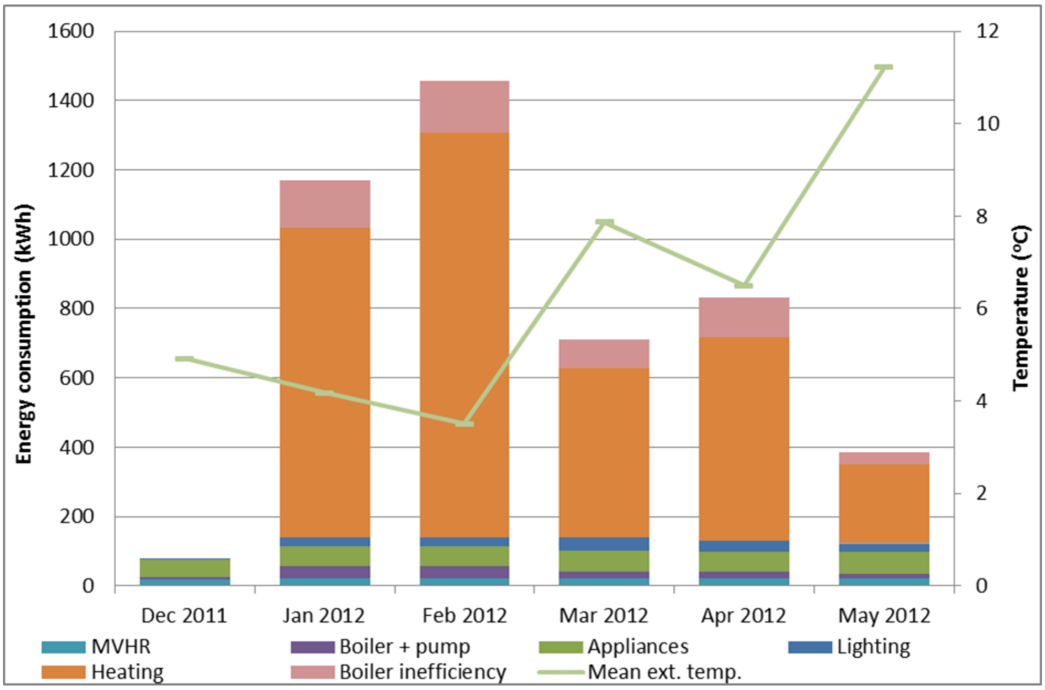


Figure 10. House A: Monthly energy consumption by end use

3.2.2 House B

Appliance consumption represents around half of all energy consumption in autumn (October/November), mainly due to extremely high appliance consumption in October. Thereafter, appliance consumption was somewhat reduced, and heating consumption increased, so the winter and spring plots show a different proportion, with heating accounting for over half of energy usage. End uses associated with space heating also include the energy required for boiler control and operation and pump operation, as well as boiler inefficiency. Boiler inefficiency is calculated by subtracting the total boiler energy output for heating and hot water from the energy supplied to the boiler.

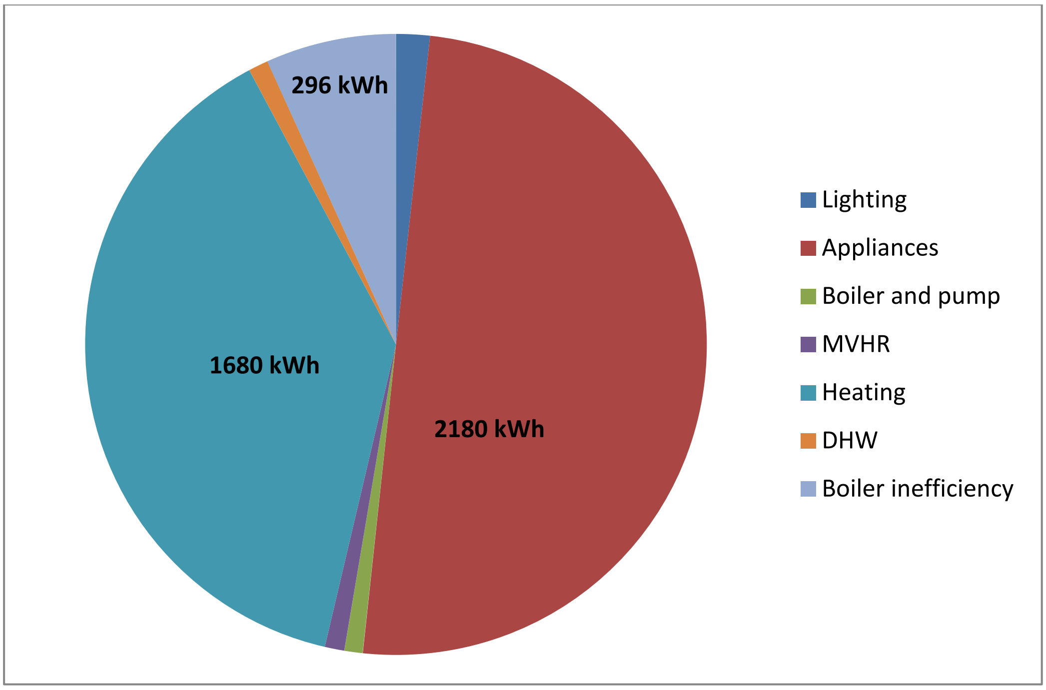


Figure 11. House B: Autumn energy consumption by end use (October and November 2012).

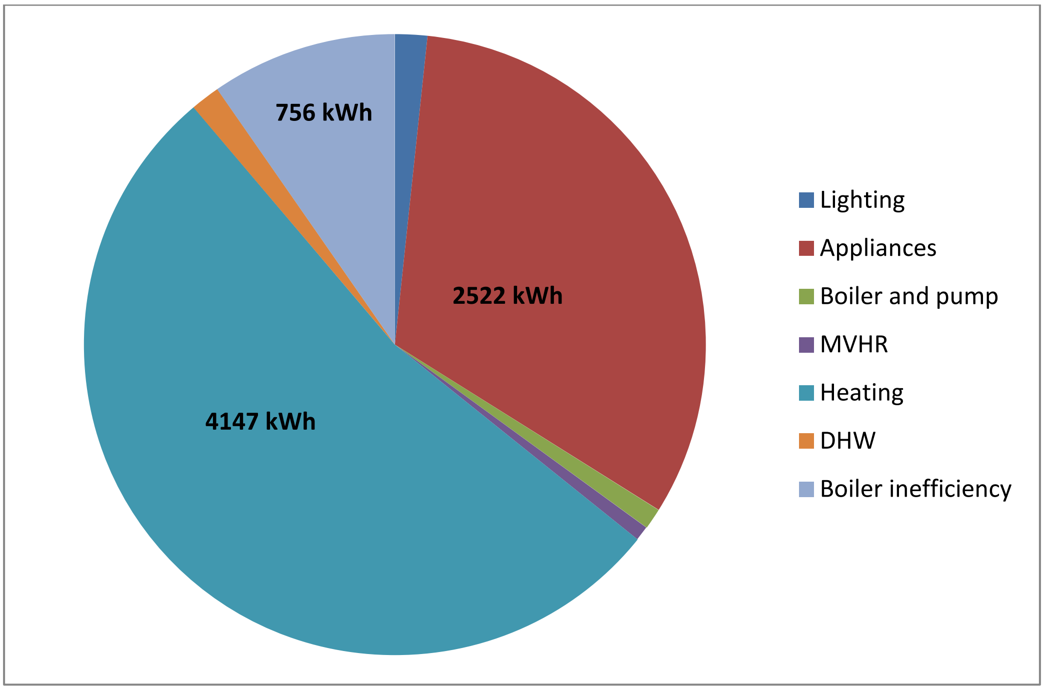


Figure 12. House B: Winter energy consumption by end use (December 2012 – February 2013).

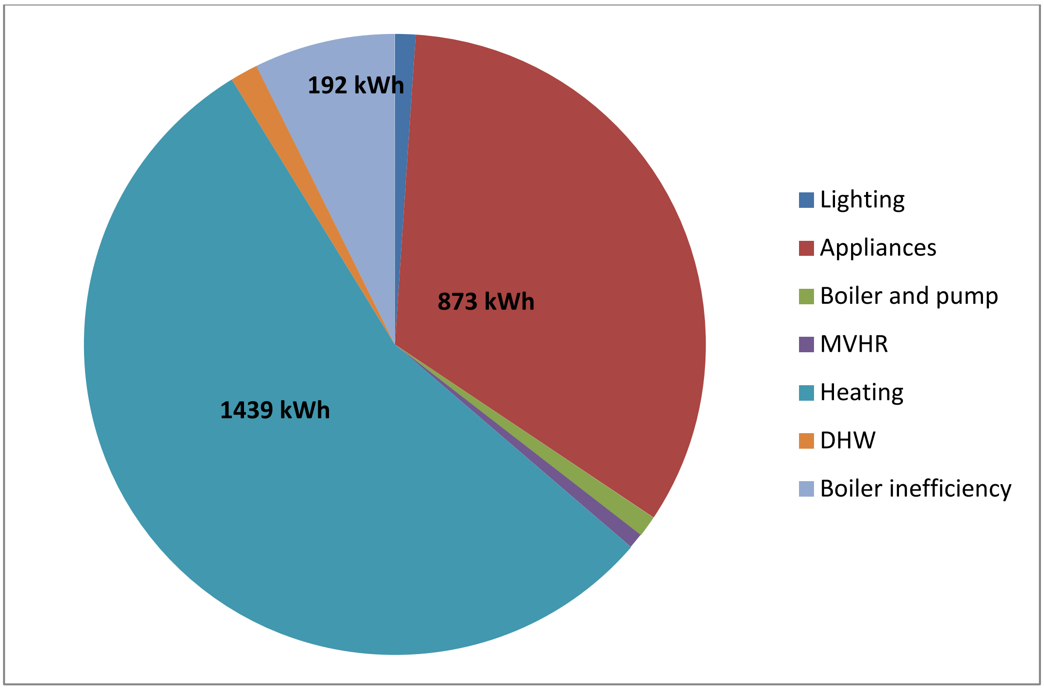


Figure 13. House B: Spring energy consumption by end use (March 2013).

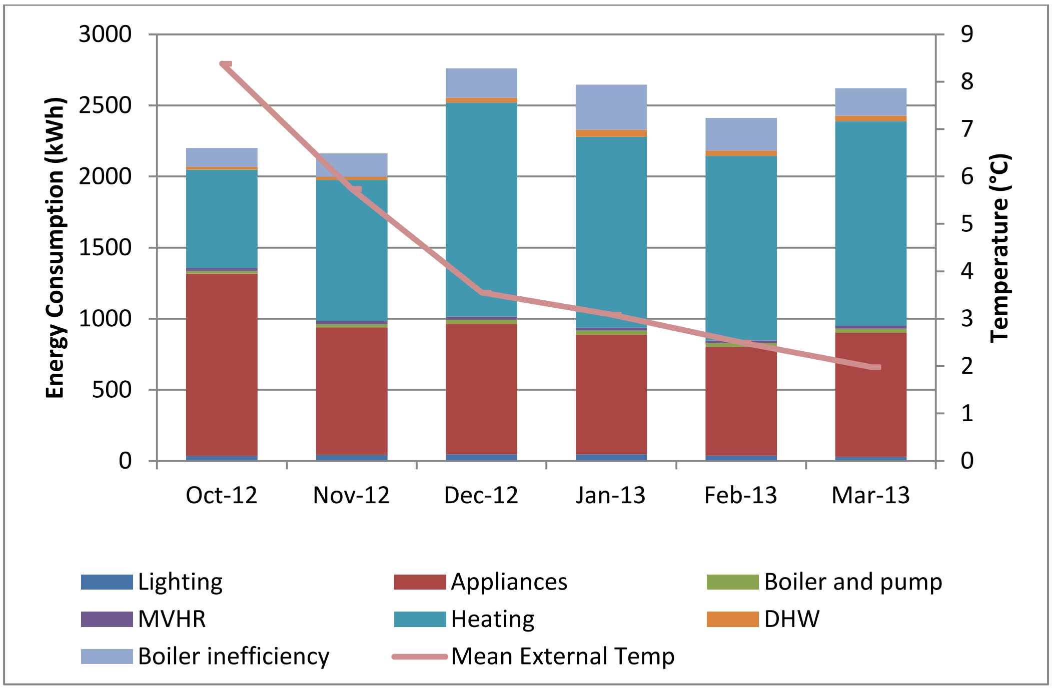


Figure 14. House B: Monthly energy consumption by end use.

The continued high consumption for heating during March is explained by the fact that temperatures remained very cold. Indeed the average monthly temperature for March 2013 was the lowest of all the months shown (1.98 compared with 3.55, 3.09 and 2.5 for December 2012, January and February 2013 respectively).

3.3 Total electricity by end use

3.3.1 House A

Total electricity consumption from January onwards was broadly stable, as illustrated in Figure 15.

Appliance consumption is primarily dominated by the operation of the fridge/freezer. The small increase in appliance energy consumption from January onwards can be attributed to the heating system raising the mean internal temperature of the dwelling, resulting in a greater temperature differential between the interior and the exterior of the fridge/freezer. The net effect of this is an increase in the electrical consumption associated with the fridge/freezer.

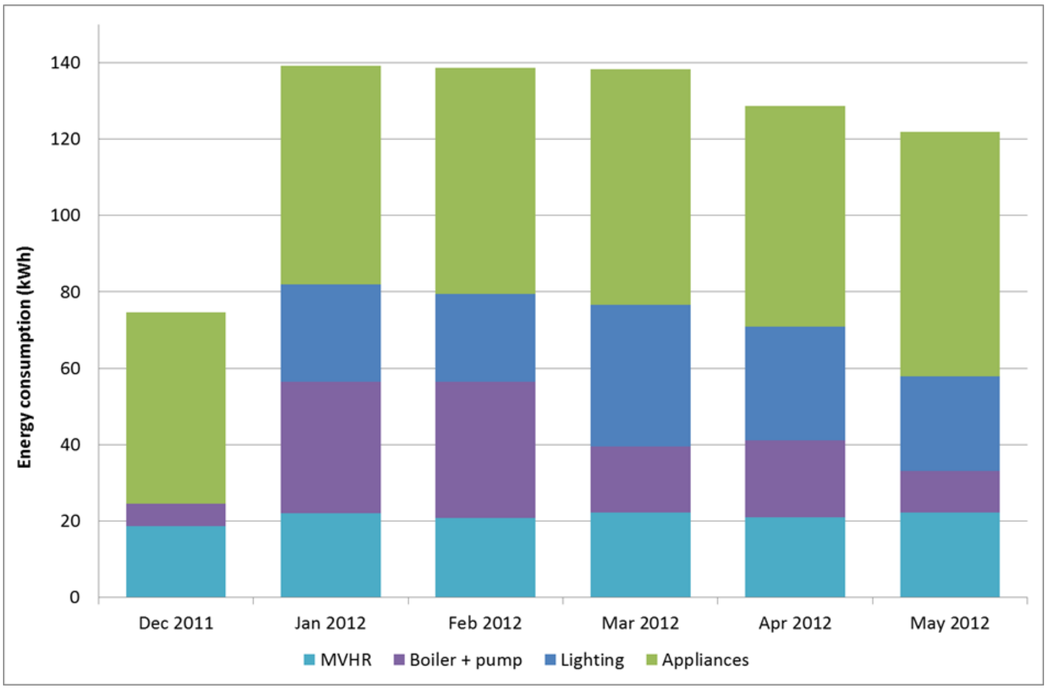


Figure 15. House A: Monthly total electricity consumption by end use

Electrical energy consumption was similarly apportioned between seasons, illustrated in Figure 16 and Figure 17. The difference is primarily the result of the reduction in space heating demand in spring, reducing boiler and pump use; this was compensated by an unexpected rise in lighting consumption. Lighting consumption was expected to decrease as daylight hours extended, due to declining operation of the photo-sensitive outside light.

However, from March onwards, there were prolonged periods where first or second floor lighting was left on, accounting for the increase in lighting consumption.

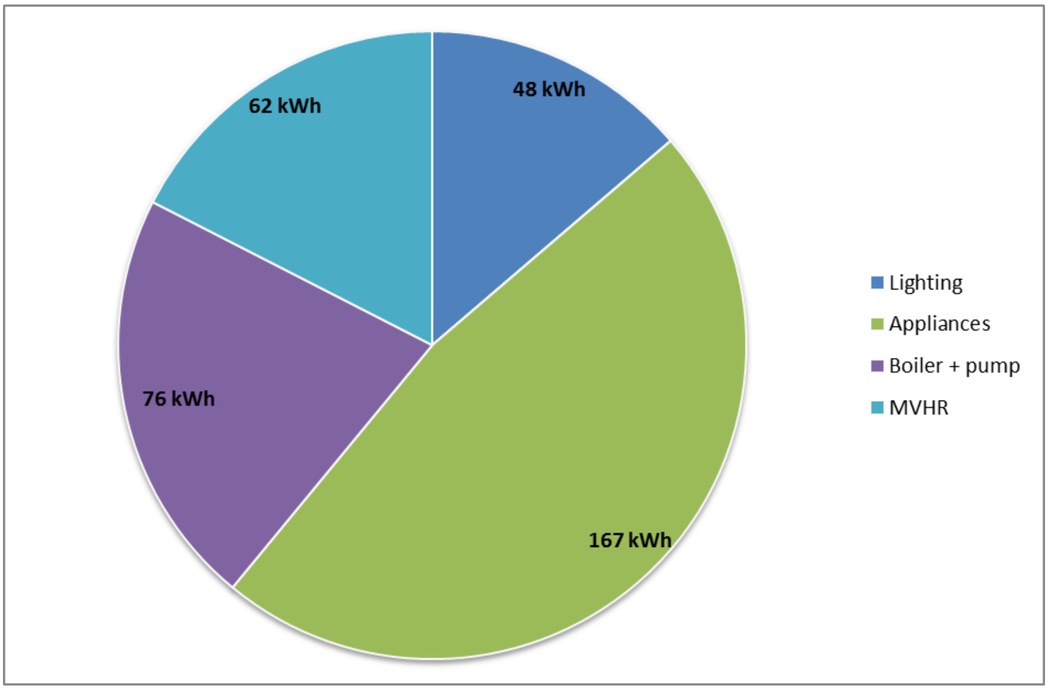


Figure 16. House A: Winter 2011/12 electricity consumption by end use

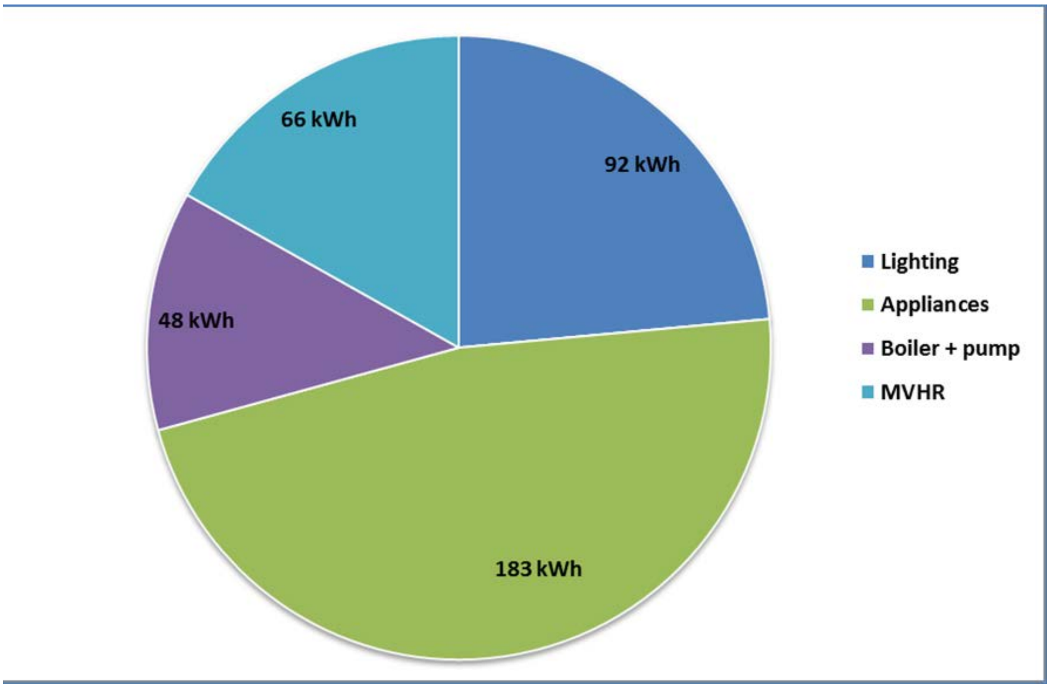


Figure 17. House A: Spring 2012 electricity consumption by end use

It is evident from Figure 18 that the PV array did not generate enough energy over the course of any month to offset the dwellings electricity consumption; this is unsurprising given that the array is rated 0.658 kWp.

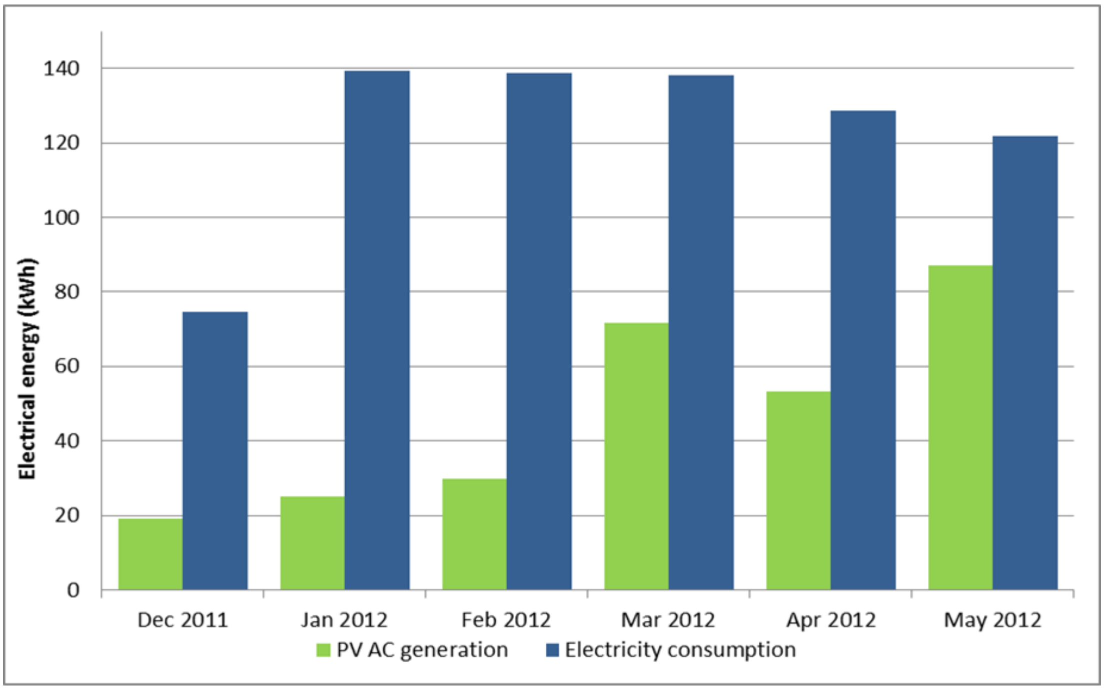


Figure 18. House A: PV AC electricity generation vs. electricity consumption

3.3.2 House B

Electricity consumption for House B was dominated by the consumption from appliances, as illustrated in Figure 19. This includes the oven and hob, all socket circuits, the doorbell, the alarm system and also a disability lift. However, the latter used somewhat less than 1kWh daily, and so was not responsible for the high appliance usage. In fact, the vast majority could be accounted for by the consumption of appliances plugged into the socket circuits.

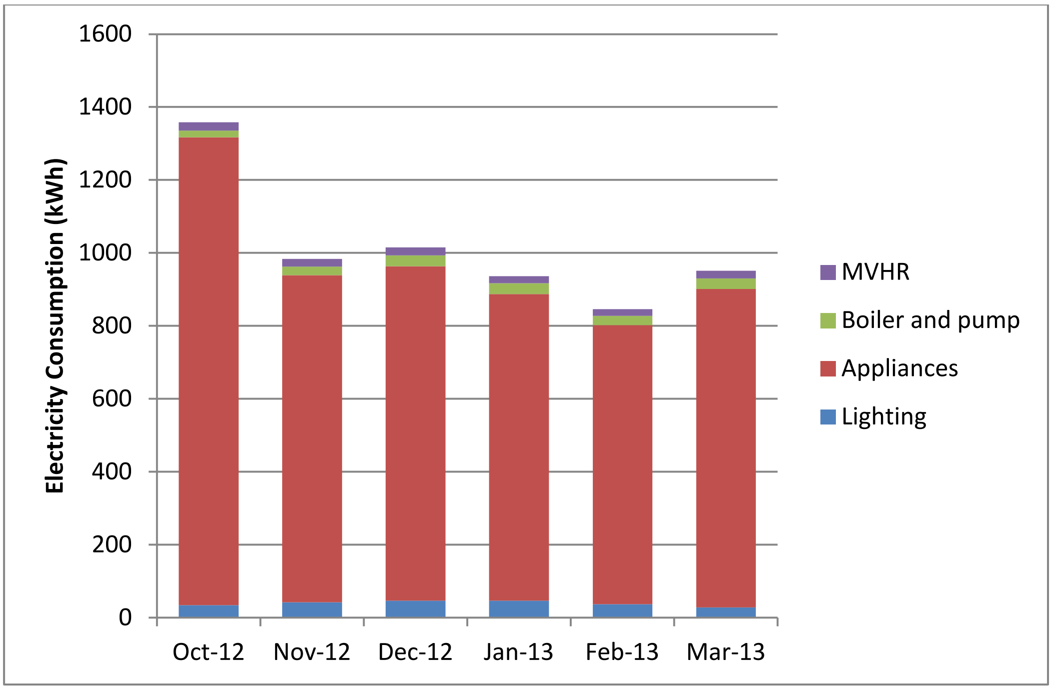


Figure 19. House B: Monthly electricity consumption by end use.

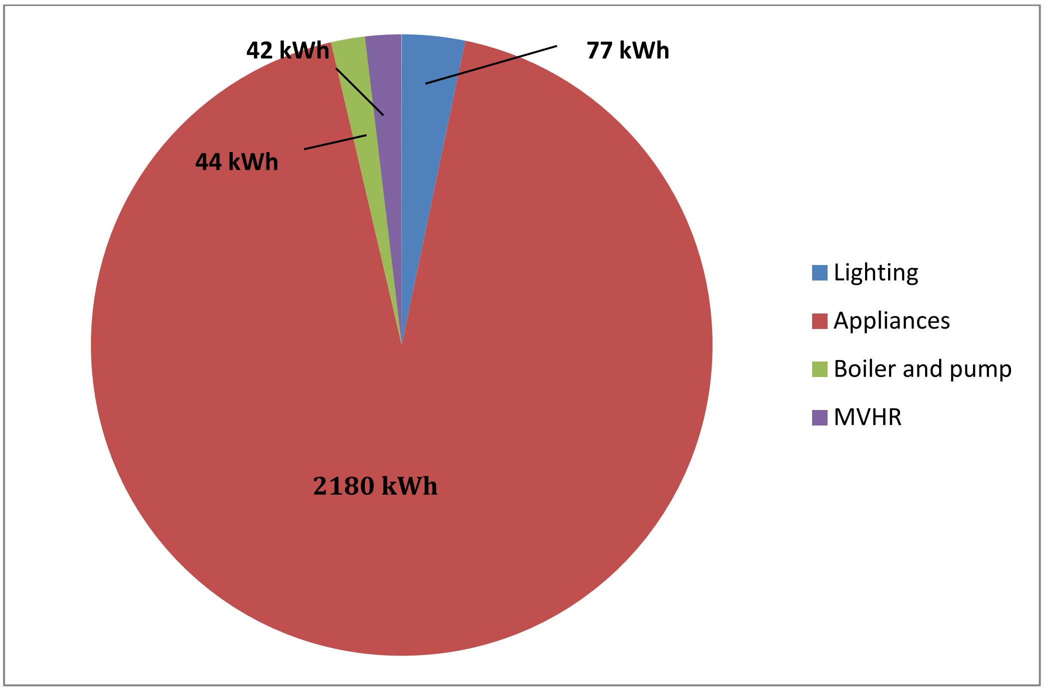


Figure 20. House B: Autumn electricity consumption by end use (October/November 2012).

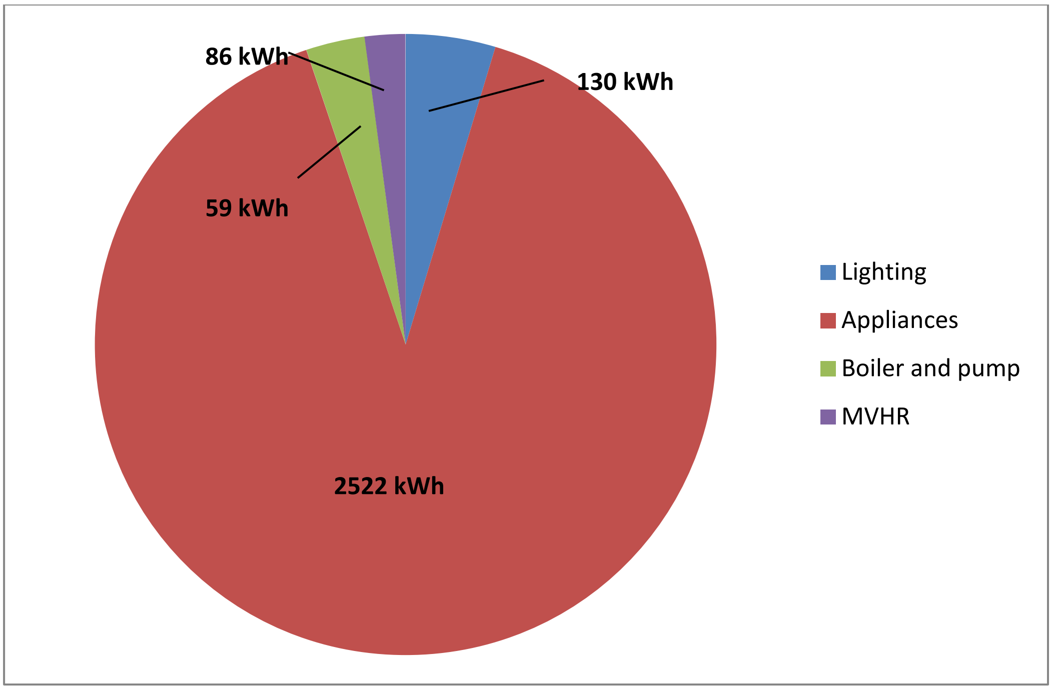


Figure 21. House B: Winter electricity consumption by end use (December 2012 – February 2013).

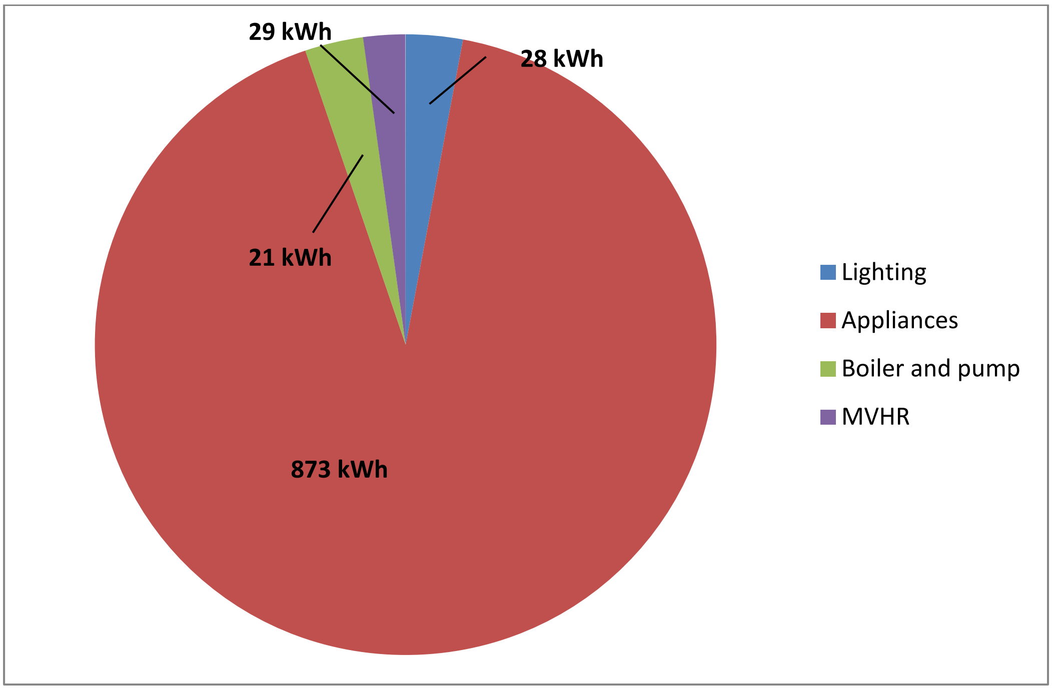


Figure 22. House B: Spring electricity consumption by end use (March 2013).

Boiler consumption increases in winter and spring (the latter as a result of the cold March weather discussed earlier). Also as expected, lighting accounts for a somewhat greater proportion over the winter period due to the reduction in daylight hours.

Since the array is rated at only 0.658 kWp, the quantity of electricity generated is small compared with the total house consumption. Although generation in March was higher than for House A in the previous March, House B was fully occupied and therefore had a far greater total electricity consumption also. Thus even in March, the PV array generated only the equivalent of around 13% of the total electricity consumption (see Figure 23 below).

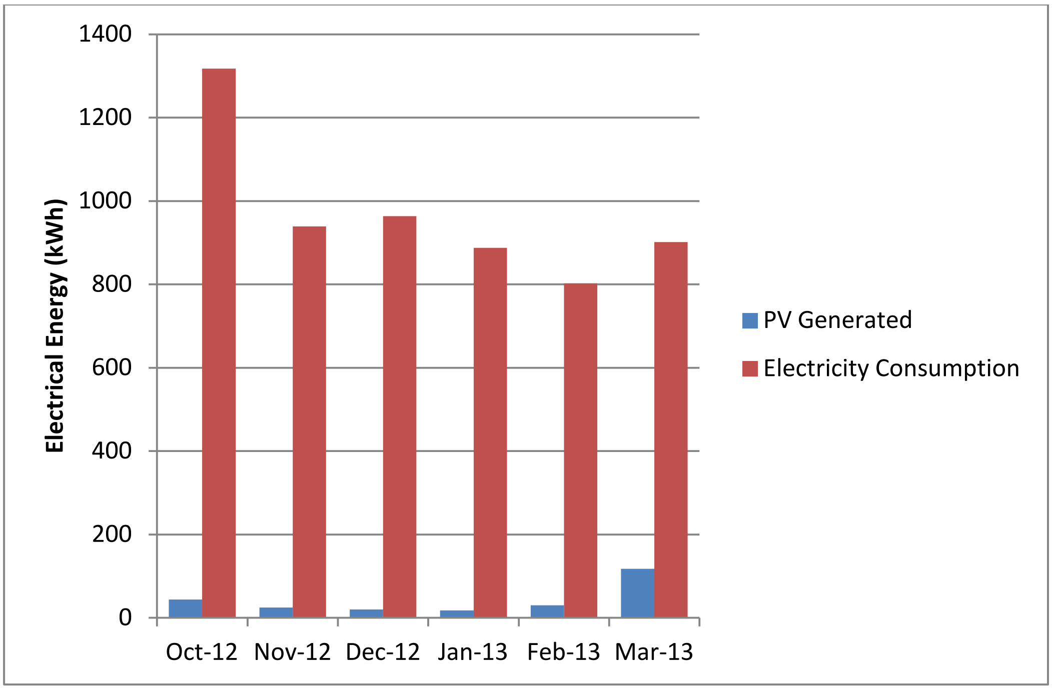


Figure 23.House B: PV AC electricity generation and total house electricity consumption.

3.4 Energy demand: average daily profiles

3.4.1 House A

As House A was unoccupied, the MVHR system was not called upon to use the boost setting, which resulted in similar consumption rates throughout the day, illustrated in Figure 24. MVHR electricity demand in December is lower due to an unexplained period of low demand between the 17/12 and 21/12 inclusive, as can be seen in Figure 25.

The increasing hours of daylight as monitoring progresses are evident in Figure 26; this is characterised by a shortening of the overnight lighting demand period, triggered by the photo-sensitive outdoor light. Daytime demand is sporadic, potentially caused by intermittent occupancy of the dwelling at varying times.

The daily electricity demand profiles in Figure 27 highlight the central heating cycle in operation. Demand picks up from the overnight baseload of approximately 7W, then spikes as the heating systems attempts to compensate for overnight cooling within the dwelling. Demand is lower in January as the heating system was only operational for 20 days; however the demand is more consistent throughout the day. The night time baseload represents the power required by the boiler while in standby.

The lower December and January appliance demand seen in Figure 28 is due to lower internal temperatures resulting in less demand from the fridge/freezer.

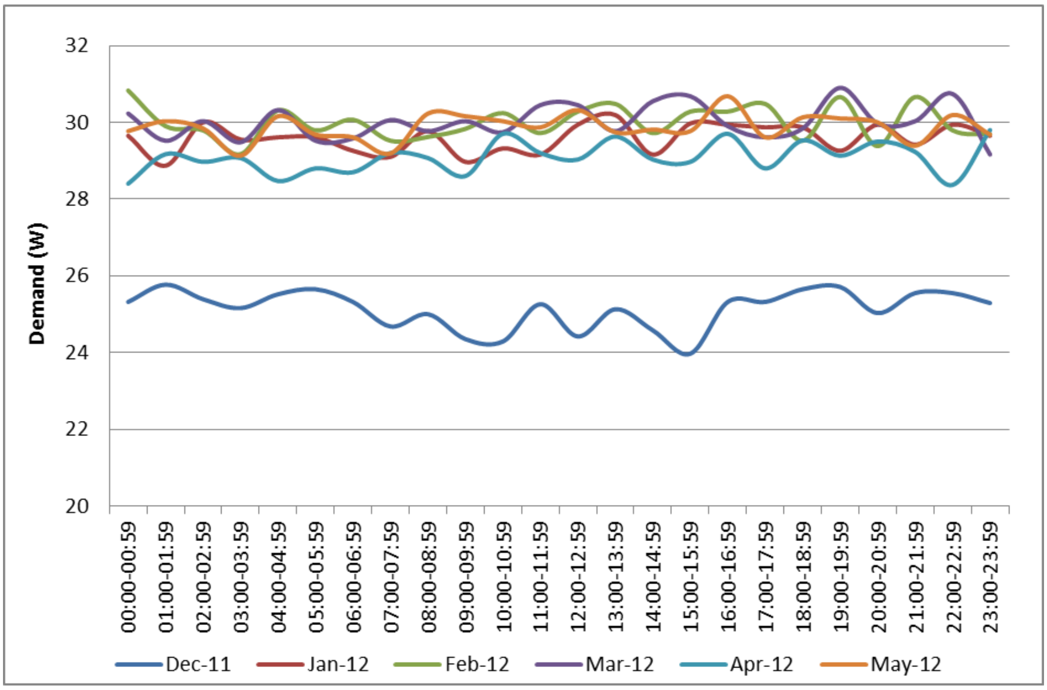


Figure 24. House A: Electricity demand – MVHR

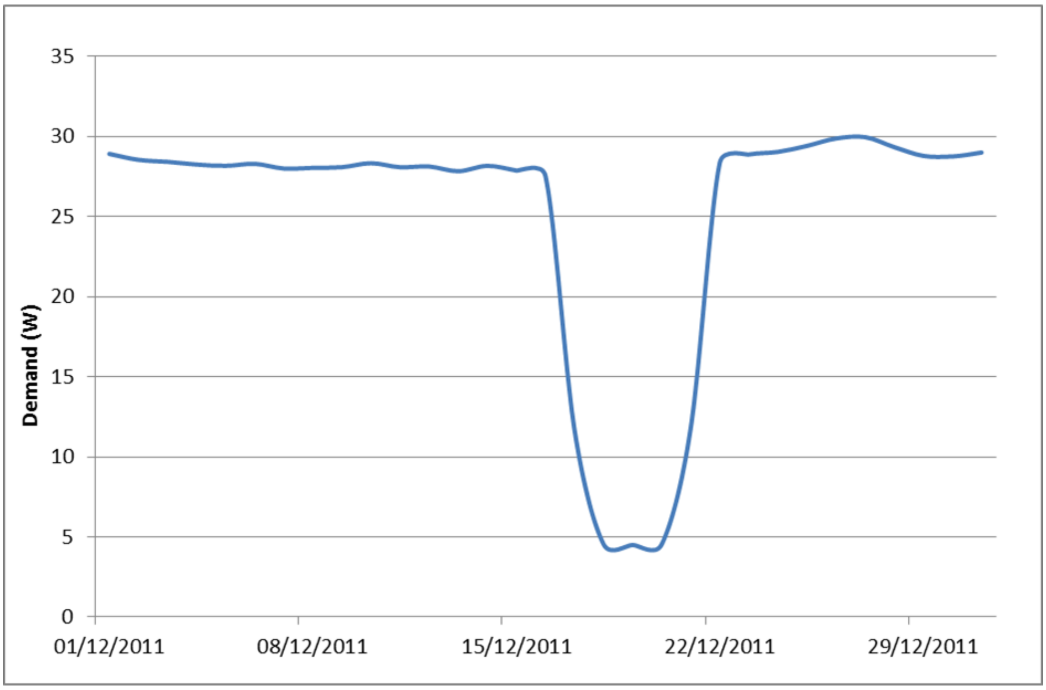


Figure 25. House A: December 2011 MVHR demand

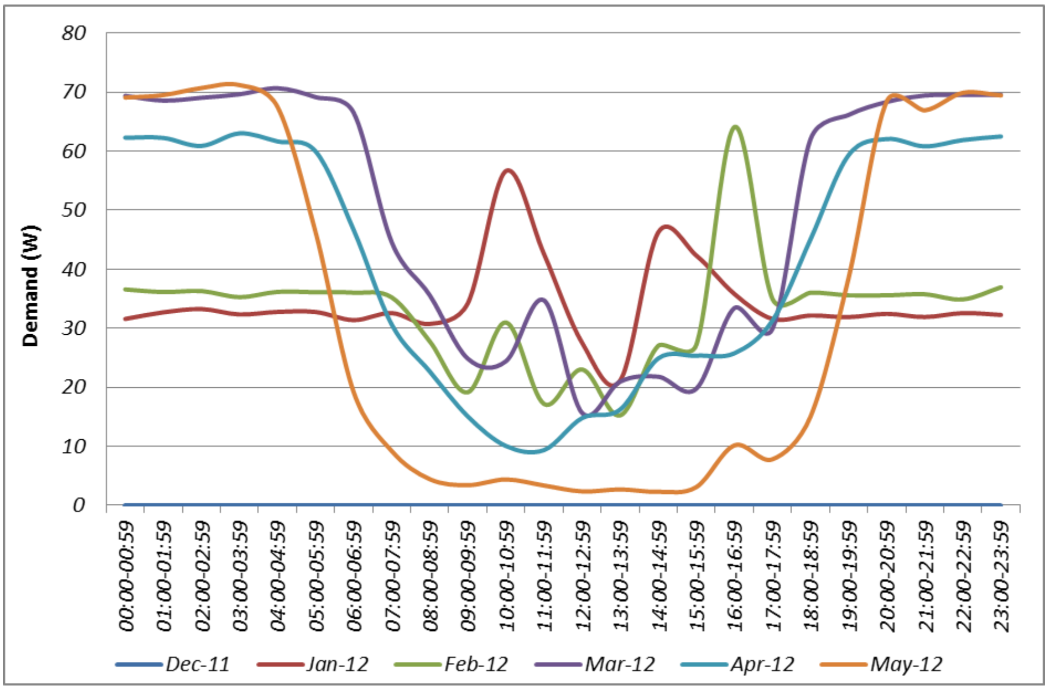


Figure 26. House A: Electricity demand – Lighting

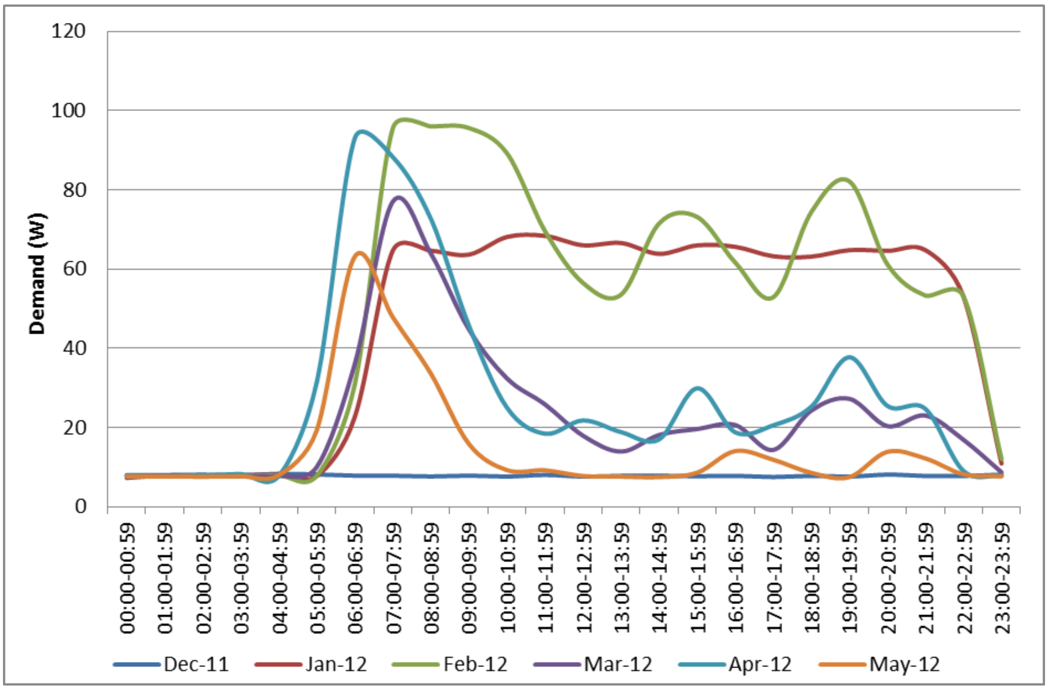


Figure 27. Electricity demand – Boiler and central heating pump

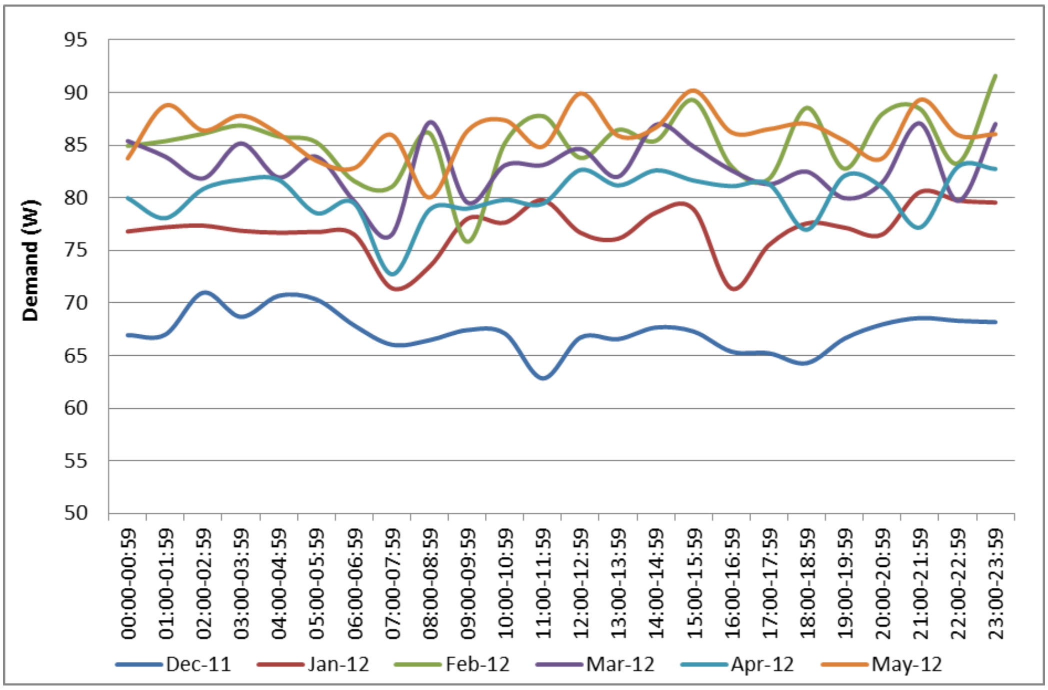


Figure 28. House A: Electricity demand – Appliances

3.4.2 House B

MVHR demand remained fairly steady throughout the day for all months, as seen in Figure 29.

The lighting profile shows a peak during the morning (around 7-10 am), with a larger and longer peak during the evening (between around 4pm and 1 am), seen in Figure 30. The evening peak displays a tendency to begin later in the months with longer hours of daylight, and also to consume somewhat less energy overall.

Appliance usage takes place throughout the daytime, with a high baseload in October (around 1 kW) dropping to a value of less than 0.5 kW in the subsequent months (see Figure 31). It is not known whether or not this may have been as a result of energy advice given to the occupants from outside sources, but certainly the lower baseload persists over the remaining monitoring period. Therefore if the change was a result of advice given, this suggests that the effect on occupant behaviour was positive.

Boiler and pump electricity consumption is evident throughout the day from around 6.30 - 7am, with a constant overnight baseload of around 10 W. October and November show the lowest usage, which is consistent with the fact that these months had the highest mean external temperature (see Figure 32).

Domestic hot water usage shows a clear peak in the morning, together with more diffuse usage throughout the late afternoon and evening hours (see Figure 33).

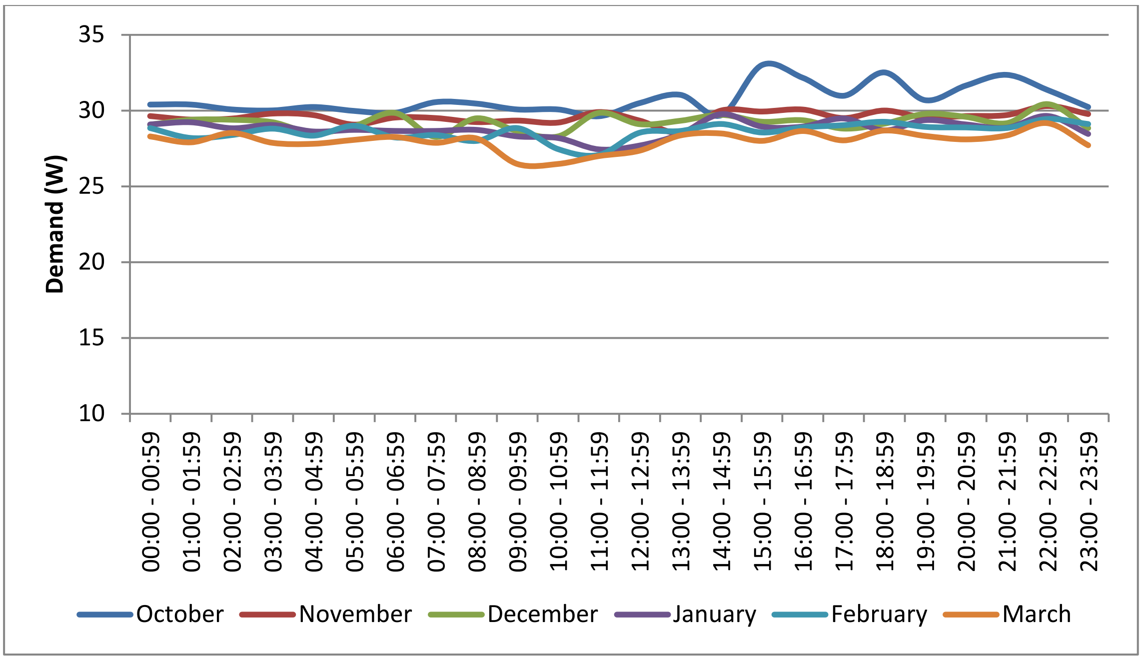


Figure 29.House B: Daily demand profile, MVHR system.

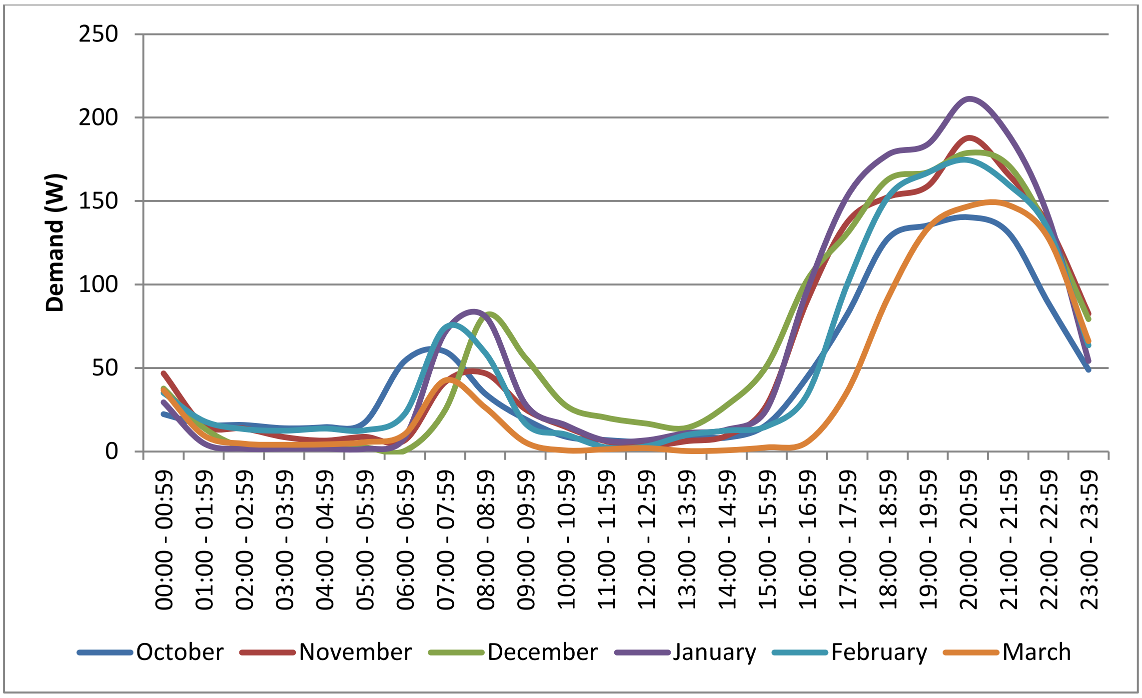


Figure 30.House B: Daily demand profile, Lighting.

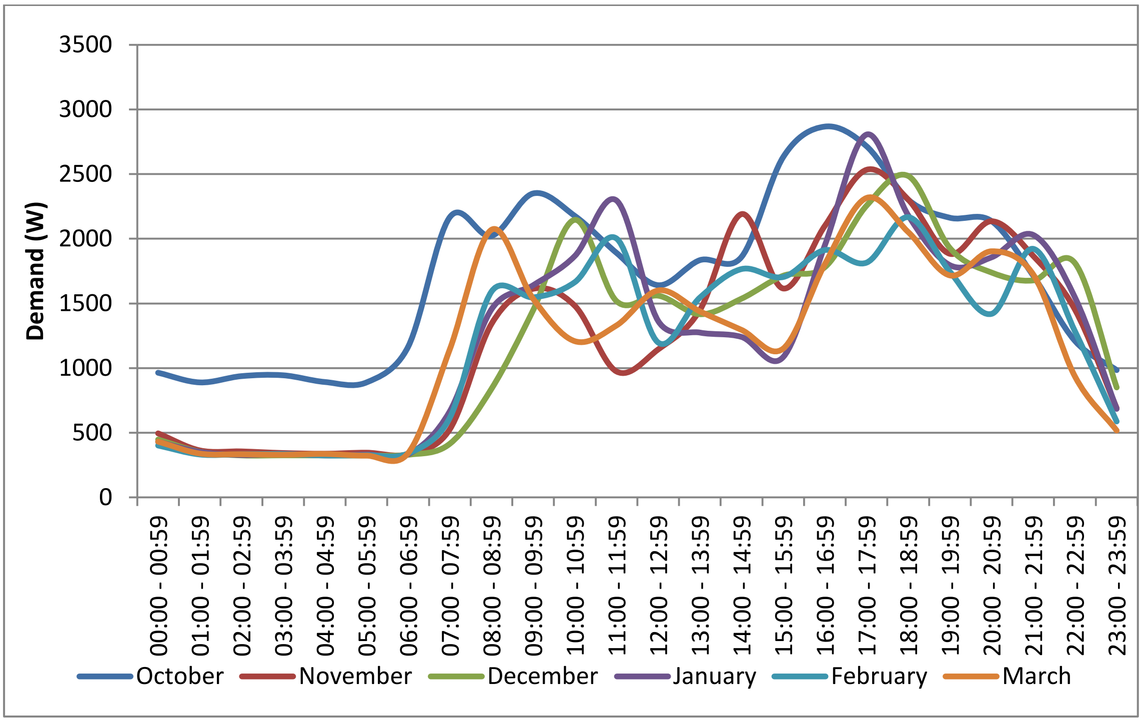


Figure 31.House B: Daily demand profile, Appliances.

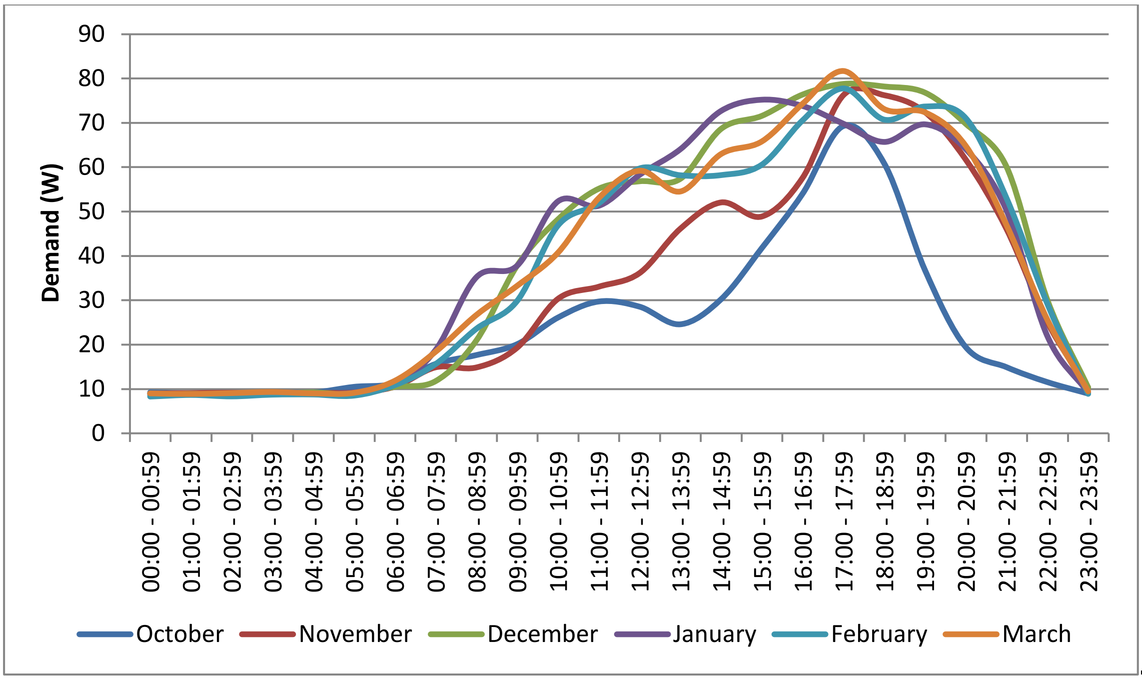


Figure 32.House B: Daily demand profile, Boiler and pump.

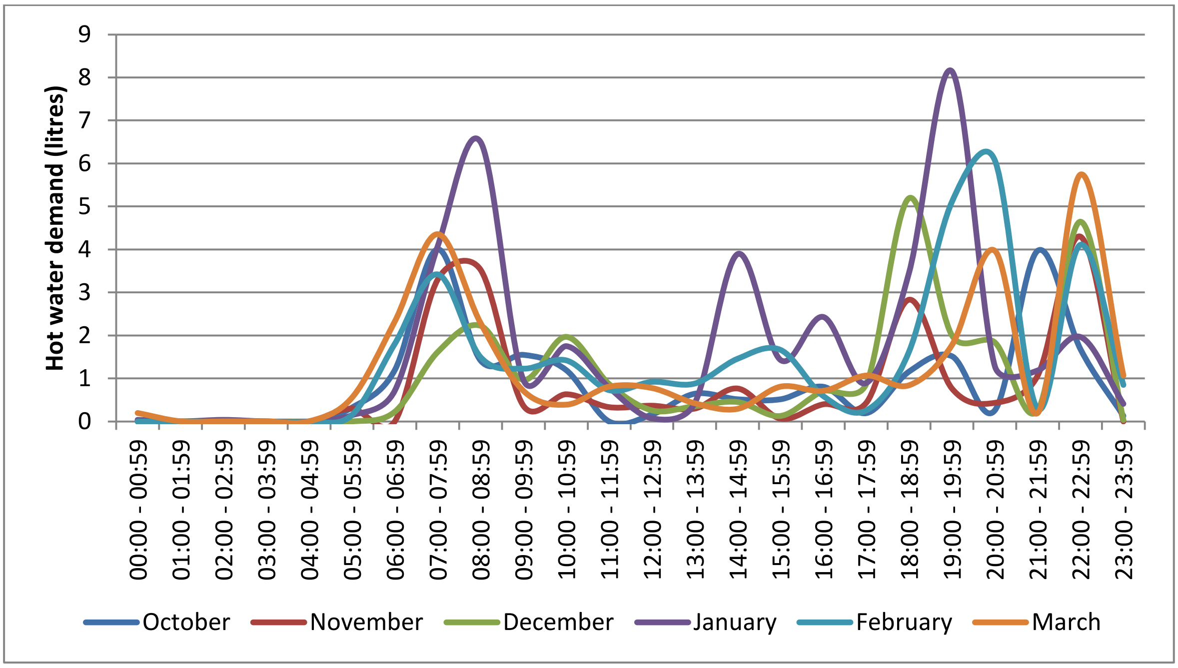


Figure 33.House B: Daily demand profile, DHW usage.

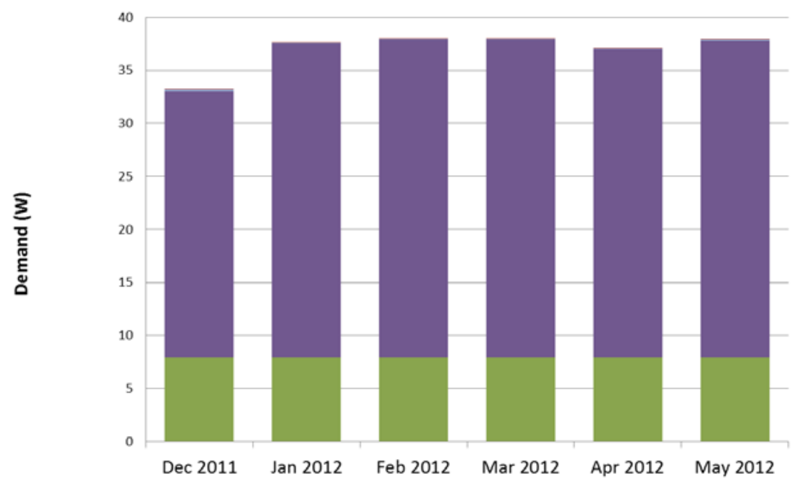
3.5 Electricity use: baseload

3.5.1 House A

Baseload power demand for House A is illustrated in Figure 34. The baseload value excludes appliance consumption as the number of appliances within the dwelling is unrepresentative of an occupied dwelling. This baseload represents the standby of systems integral to the operation of the dwelling.

The average baseload demand for House A is approximately 38W (excluding December), equivalent to 0.9kWh daily electricity consumption. Baseload demand is primarily constituted from MVHR in trickle mode and boiler in standby mode. Boiler baseload throughout the reporting period was based on the December value, when no energy for heating or hot water was consumed; therefore all boiler demand was attributable to its stand-by value. Baseload electricity consumption was responsible for 22% of consumption during the monitoring period.

PV generation was greater than baseload demand from February onwards as illustrated in Figure 35.   Over the course of the monitoring period, PV generation was 160W greater than baseload; therefore it is highly likely that over the course of a year, the PV system is capable of generating enough energy to provide the dwellings system baseload requirement.



	Dec 2011	Jan 2012	Feb 2012	Mar 2012	Apr 2012	May 2012
Doorbell	0.001	0.001	0.004	0.011	0.008	0.003
Alarm	0.169	0.122	0.072	0.058	0.086	0.120
MVHR	25.134	29.583	30.000	30.015	29.086	29.880
Boiler (Dec standby value)	7.905	7.905	7.905	7.905	7.905	7.905

Figure 34. House A: Monthly baseload power demand

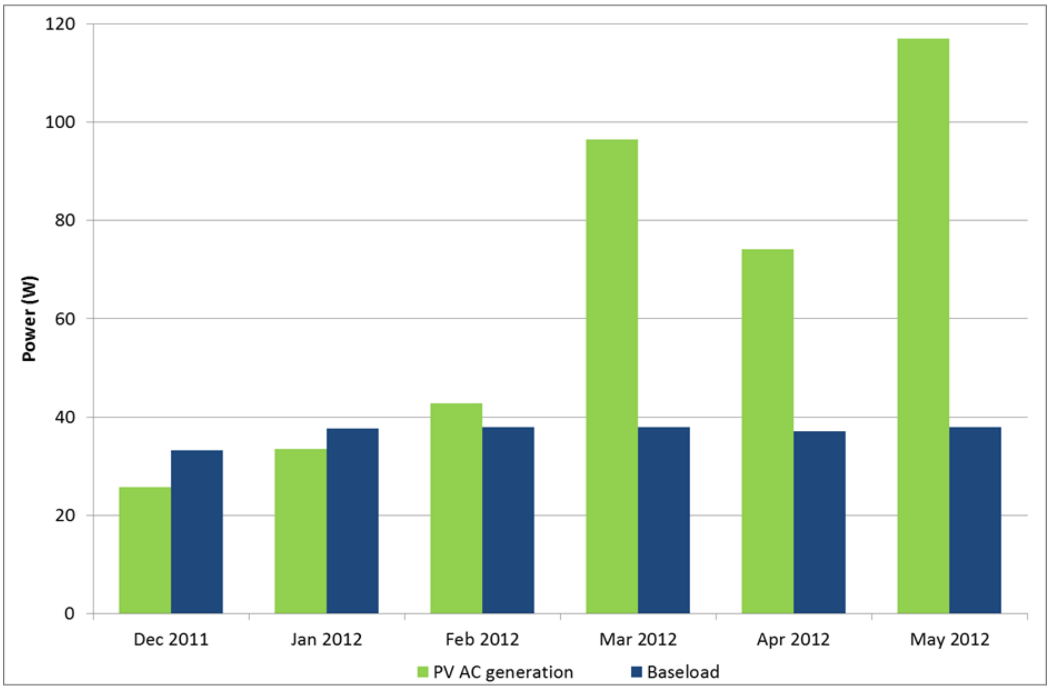


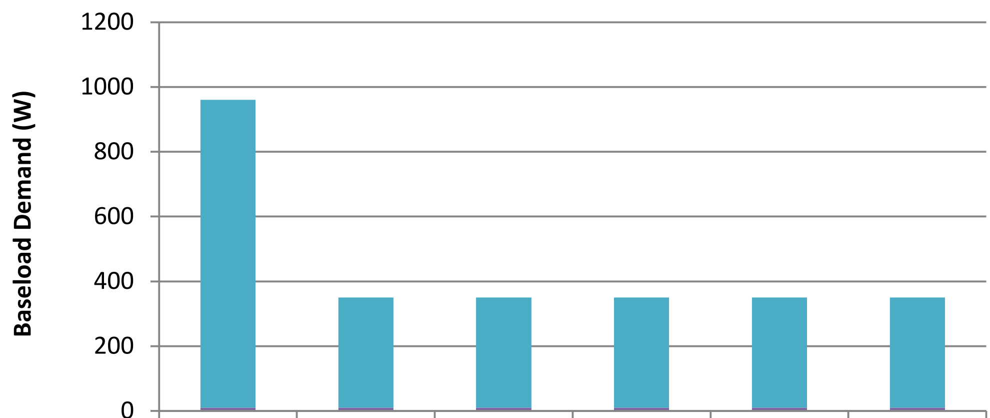
Figure 35. House A: Baseload power demand vs. PV AC generation

3.5.2 House B

Baseload power demand for House B is entirely dominated by standby appliance consumption, which is estimated from the overnight portion of the daily profile in Figure 36.

Thus the daily baseload power is around 350W for all months except October, where it is around 960W due to the higher appliance consumption. The baseload of 350W represents around 26.8% - 29.4% of total electricity consumption for November – March. The higher 960W baseload in October represents around 54% of total consumption for that month.

Figure 37 shows that in the case of House B, where appliance baseload is high, the small PV array is not capable of generating equivalent power in any of the months monitored. It is possible that it may be capable of doing so during the summer months.



	Oct	Nov	Dec	Jan	Feb	Mar
App s/b	950	340	340	340	340	340
Boiler s/b	10	10	10	10	10	10
MVHR	0.03	0.03	0.03	0.03	0.03	0.03
Alarm	0.01	0.00	0.00	-0.01	0.00	0.01
Doorbell	0.08	0.08	0.06	0.06	0.05	0.06

Figure 36.House B: Monthly baseload power demand.

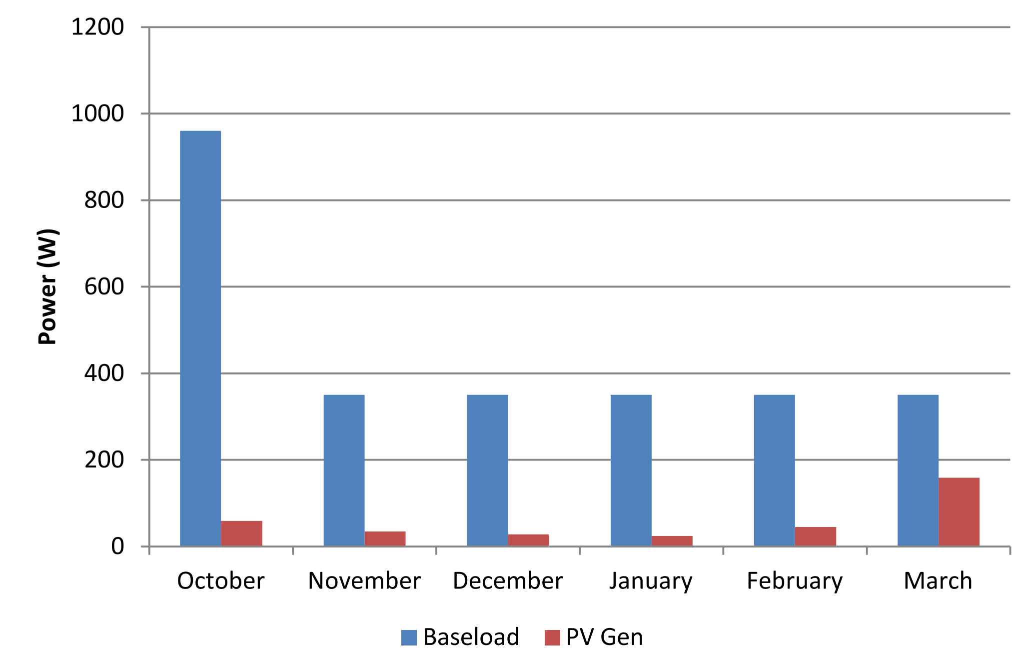


Figure 37.House B: Monthly baseload power demand and PV power generated.

3.6 System performance

3.6.1 House A

Boiler and system efficiencies are displayed in Figure 38. System efficiency includes energy consumed by the boiler and central heating pump. The system efficiency presented in the

SAP assessment is 92.1%, its SEDBUK efficiency rating is 90.1%. The SAP efficiency is almost achieved on the days with the greatest temperature difference between inside and outside.

A relationship was found between the internal and external temperature difference (delta T) and boiler/system efficiency. Boiler/system efficiency has a positive relationship with delta T, this is illustrated in Figure 39. Boiler efficiencies are influenced by the ambient air temperature of their surroundings; however the small variation in internal temperature that was measured was not found to be responsible for the variation in efficiency. Due to the lack of heating system weather compensation it is speculated that the length of boiler cycle could be the cause in efficiency variation; colder days require more consistent boiler operation resulting in greater efficiencies. The negative relationship between mean external temperature and boiler efficiency is illustrated in Figure 40.

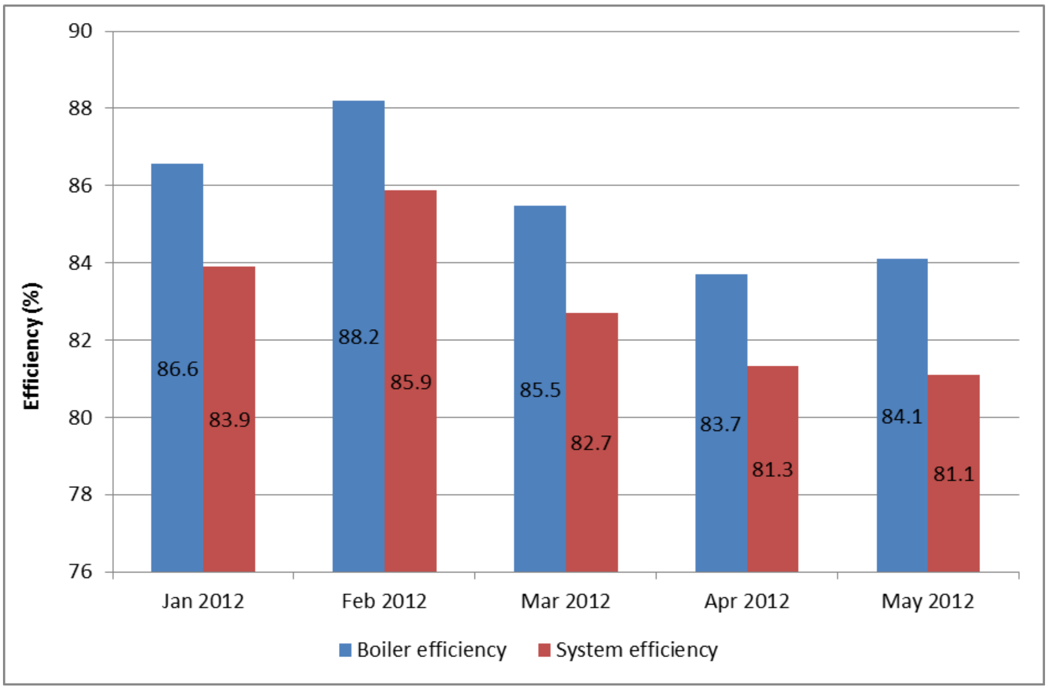


Figure 38. House A: Boiler and heating system efficiency

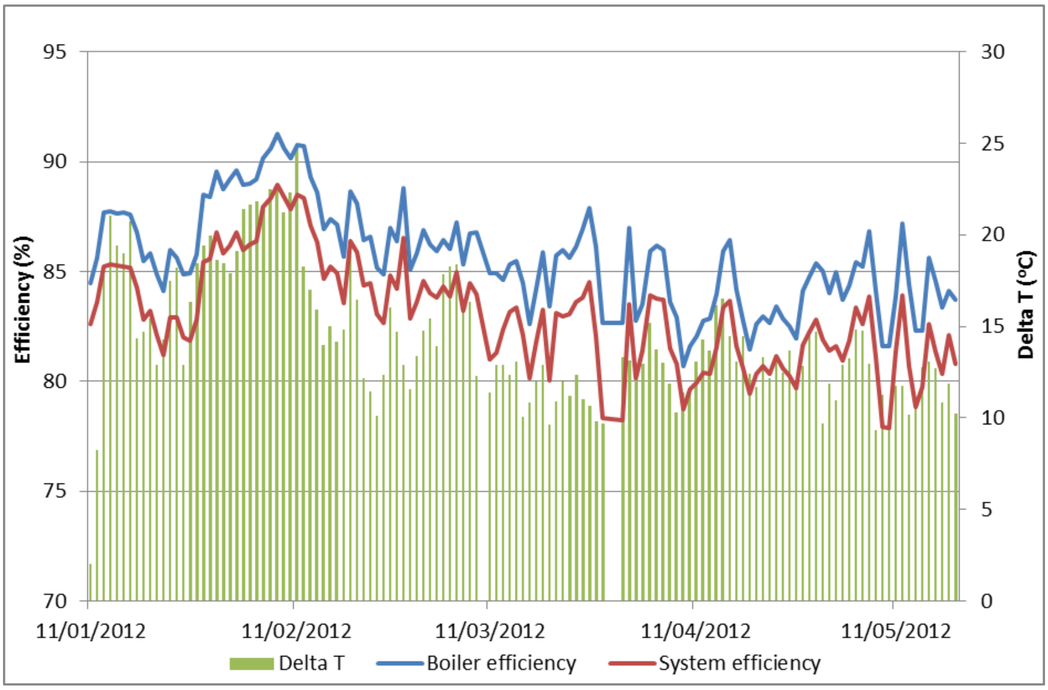


Figure 39. House A: Boiler and system efficiency vs. delta T

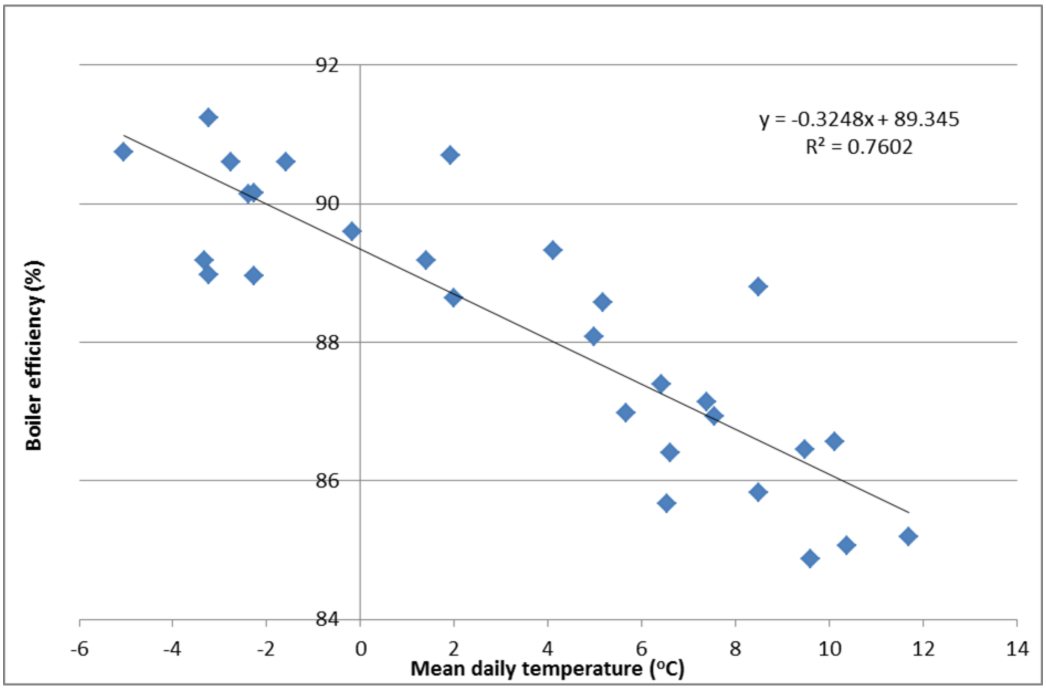


Figure 40. House A: Boiler efficiency vs. external temperature (February 2012)

MVHR duct temperature measurements, in Figure 41, indicate some pre-warming of supply air before reaching the heat exchanger as it moves through the fabric of the building. The point at which the heating system becomes operational is evident as the temperatures diverge.

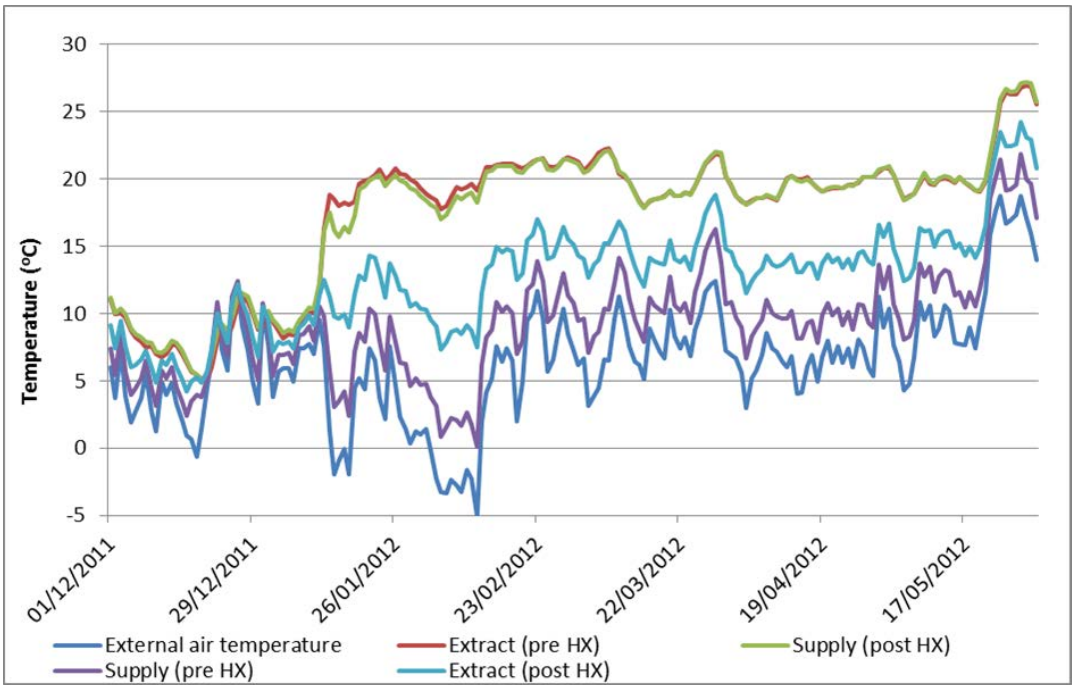


Figure 41. House A: MVHR duct measurements

Monitoring highlighted issues with the sensitivity of the thermocouples measuring duct temperatures. The extracted air (pre heat exchanger) and supply air (post heat exchanger) temperatures were occasionally within the tolerances of the thermocouples. This has resulted in some supply (post HX) temperature measurements exceeding extract (pre HX) measurements, resulting in heat exchanger efficiencies of over 100%.

Figure 42 demonstrates the relationship between delta T and heat exchanger efficiency (efficiency values have not been included due to the issues regarding thermocouple sensitivity). The efficiency of the heat exchanger is inversely proportional to the temperature difference between internal and external environments, in line with anticipated behaviour.

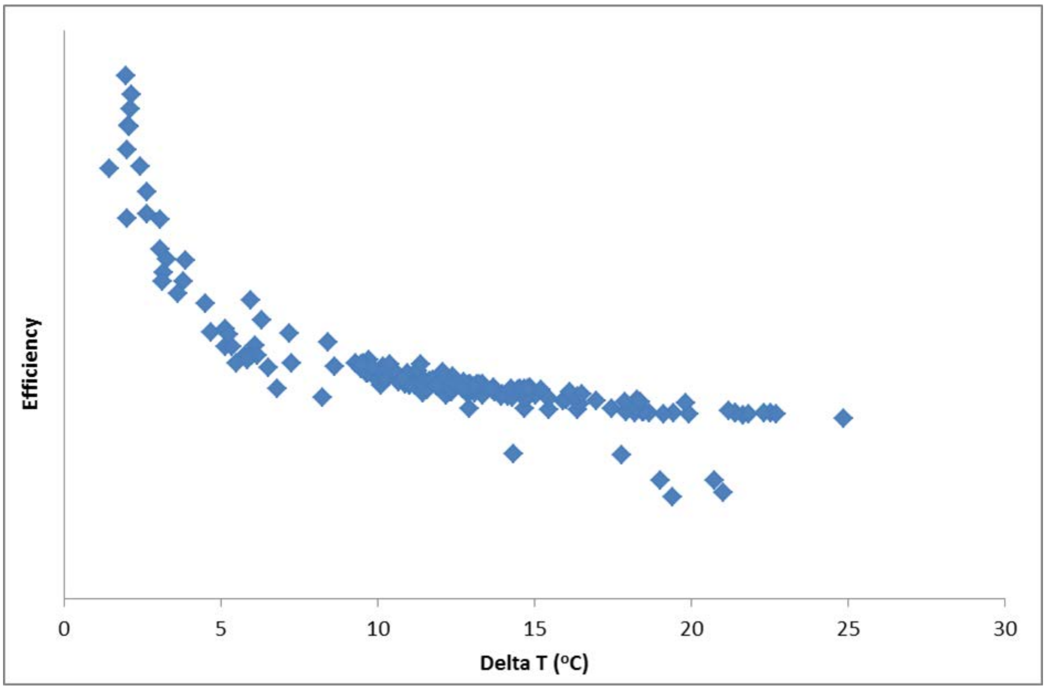


Figure 42. House A: MVHR efficiency vs. delta T

The PV array converted 13.5% of solar insolation to DC electricity, slightly higher than the manufacturers stated module efficiency of 12.4%, shown in Figure 43. Figure 44 illustrates the corresponding decrease in efficiency of the array as insolation increases; this is due to the reduction in PV cell efficiency as the operational temperature rises. Between 21/04/12 and 20/05/12 mean PV array efficiency was 22.8%. These increased efficiencies are represented by the outliers above the regression line in Figure 43. Further investigation into the environmental conditions which brought about this period of improved efficiency is recommended.

As seen in Figure 45, the PV system converted 12% of the incoming solar insolation into AC electricity following inverter loss. Figure 46 illustrates the increase in inverter efficiency as DC output increases. Manufacturers' literature is not available to compare this against, however the characteristics of this efficiency curve are typical of PV system inverters.

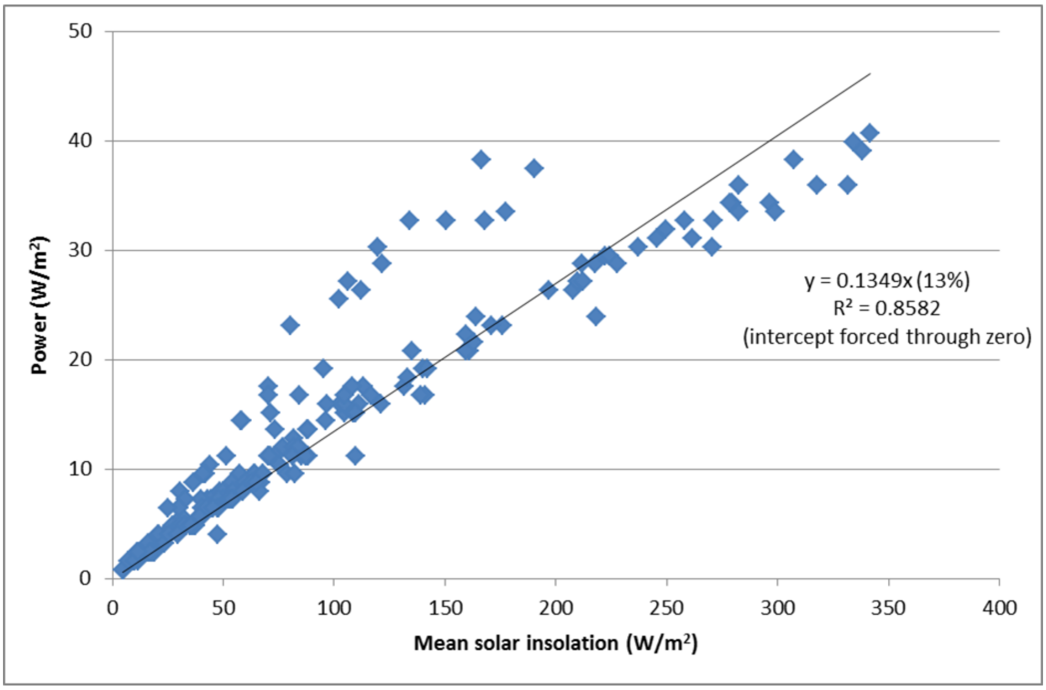


Figure 43. House A: Daily PV array conversion efficiency

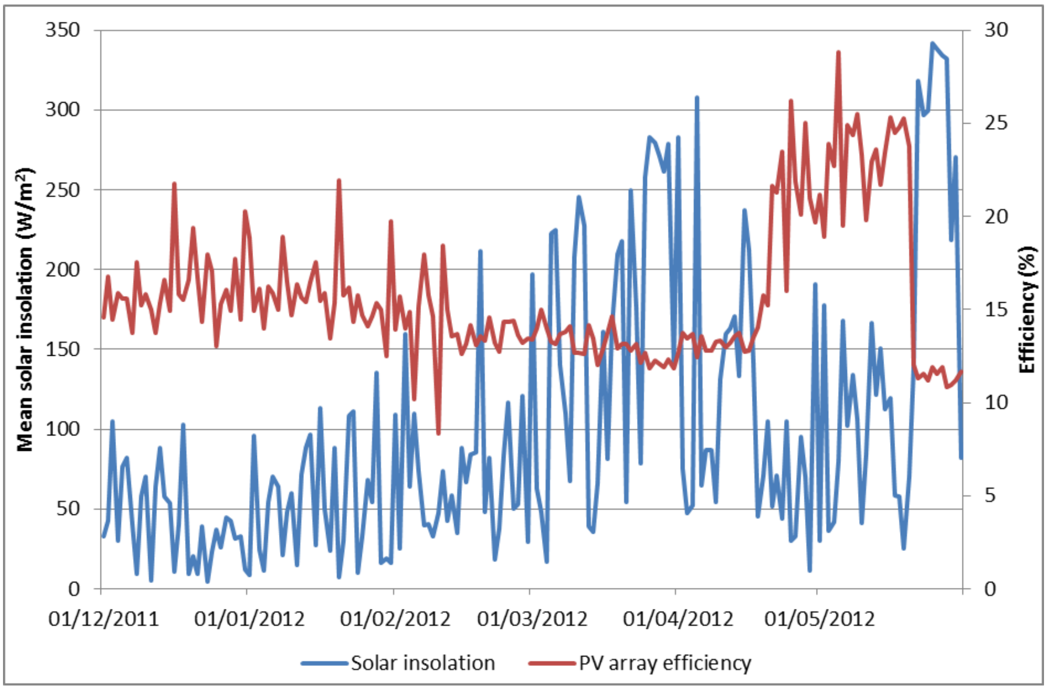


Figure 44. House A: Daily PV array conversion efficiency vs. solar insolation

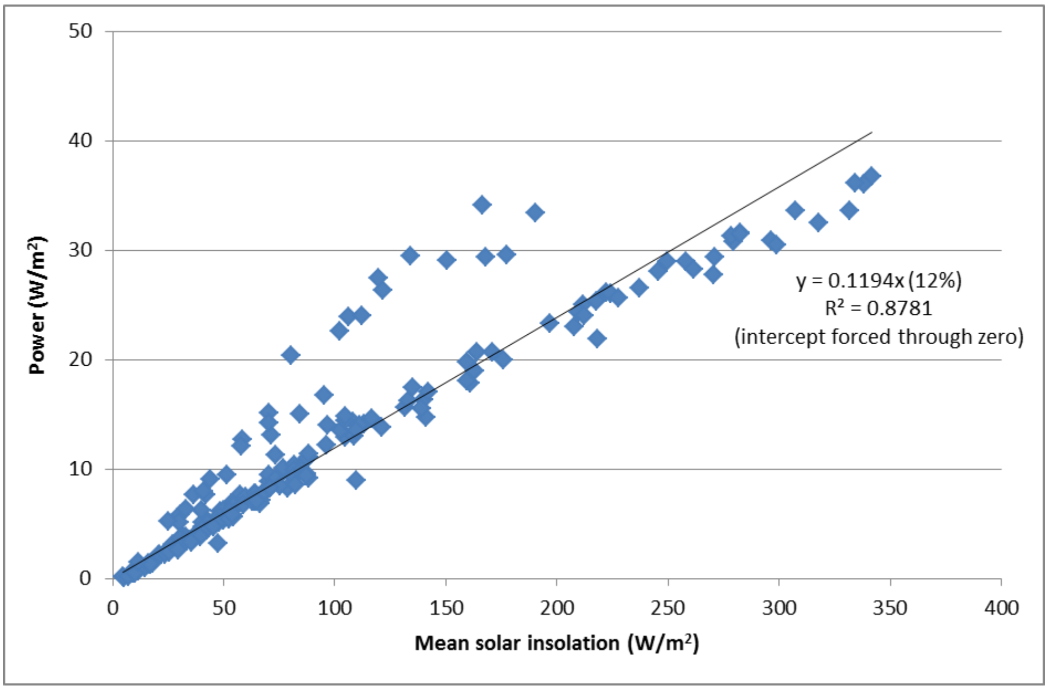


Figure 45. House A: PV system efficiency – including inverter loss

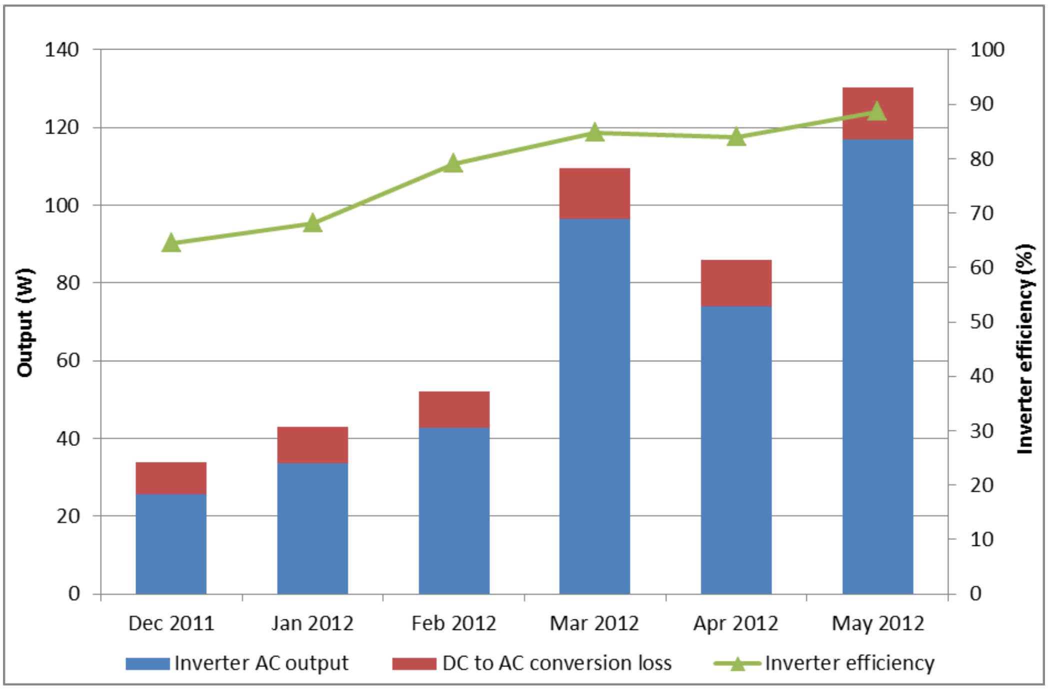


Figure 46. House A: Monthly PV power generation and efficiency

It is interesting to contrast the rise in inverter efficiency as solar insolation (and DC output) increases, illustrated in Figure 47, with the decrease in panel conversion efficiency as solar insolation increases, seen in Figure 44.

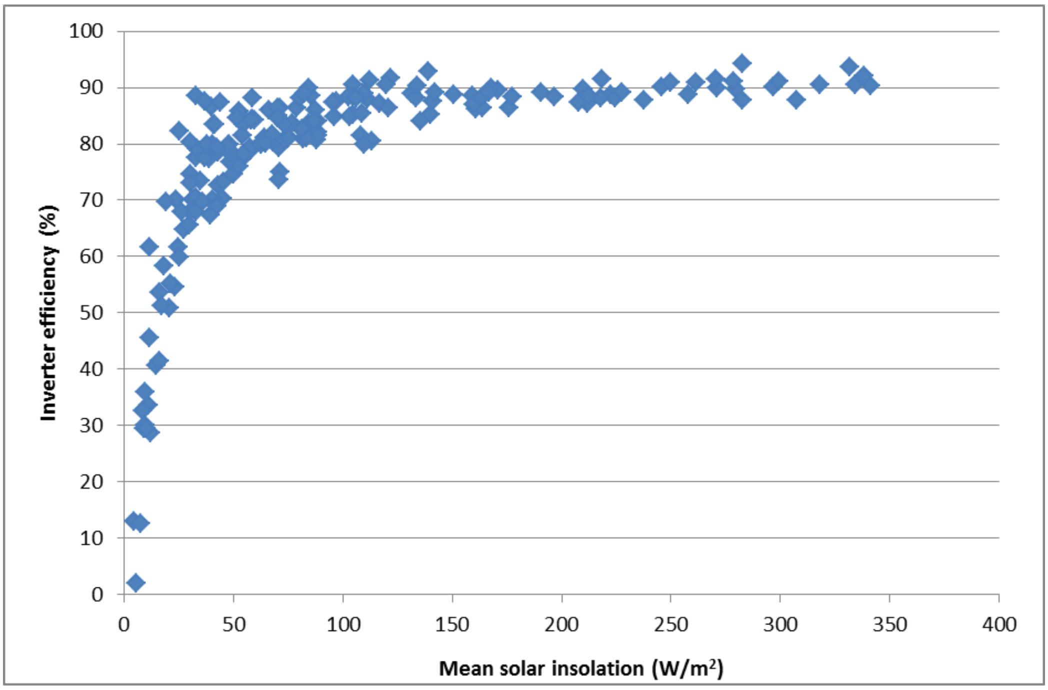


Figure 47. House A: Mean solar insolation vs. inverter efficiency

3.6.2 House B

Figure 48 shows that the boiler efficiency increases as mean external temperature decreases, with the exception of February where the efficiency is somewhat lower. However, this is mainly due to an extremely low efficiency (~10%) calculated for February 4th. The reason for this anomaly is not fully understood, but may be a result of metering difficulties following a loss of data at the beginning of the month. If Feb 4th is excluded from the calculation, the average boiler and system efficiencies for the month are calculated as 89.3 and 87.8 respectively, in line with the December values. This would then lead to a consistent boiler efficiency value of >89 for the whole period December 2012 – March 2013, which is close to the SEDBUK efficiency rating of 90.1.

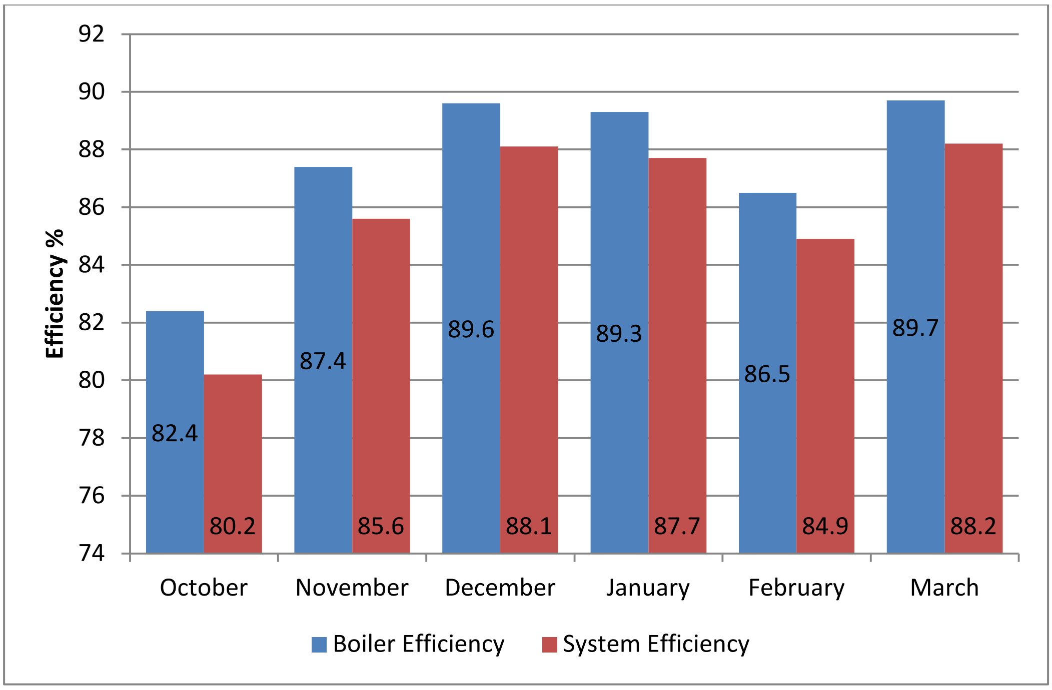


Figure 48.House B: Boiler and heating system efficiency.

As for House A, a relationship is evident between boiler efficiency and Delta-T (as may be expected if the House B internal temperatures are fairly constant and efficiency is related to external temperature (as discussed above). In Figure 49, a few days are excluded due to metering difficulties or no heat output.

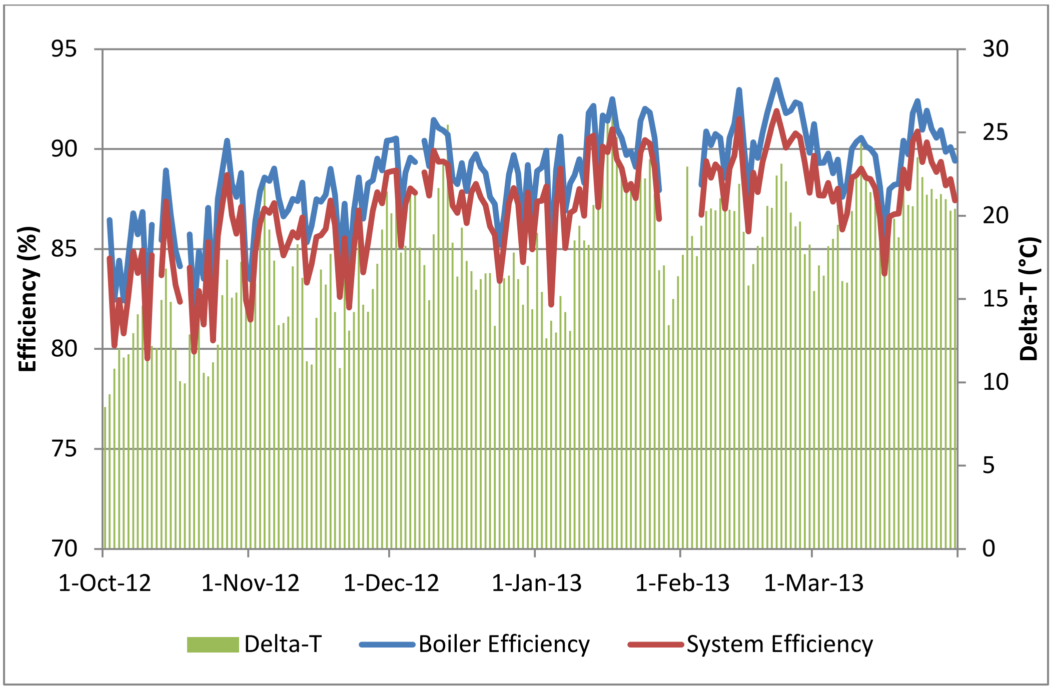


Figure 49.House B: Boiler and heating system efficiency.

If we exclude days where there was data loss (4 days), or very low values due to either heat metering difficulties or no space heating output (6 days), then there is a clear linear trend with mean external temperature (R^2 = 0.58). This gives an efficiency value at 0°C mean external temperature of 90.8 – very close to the SEDBUK efficiency rating, as seen in Figure 50 below.

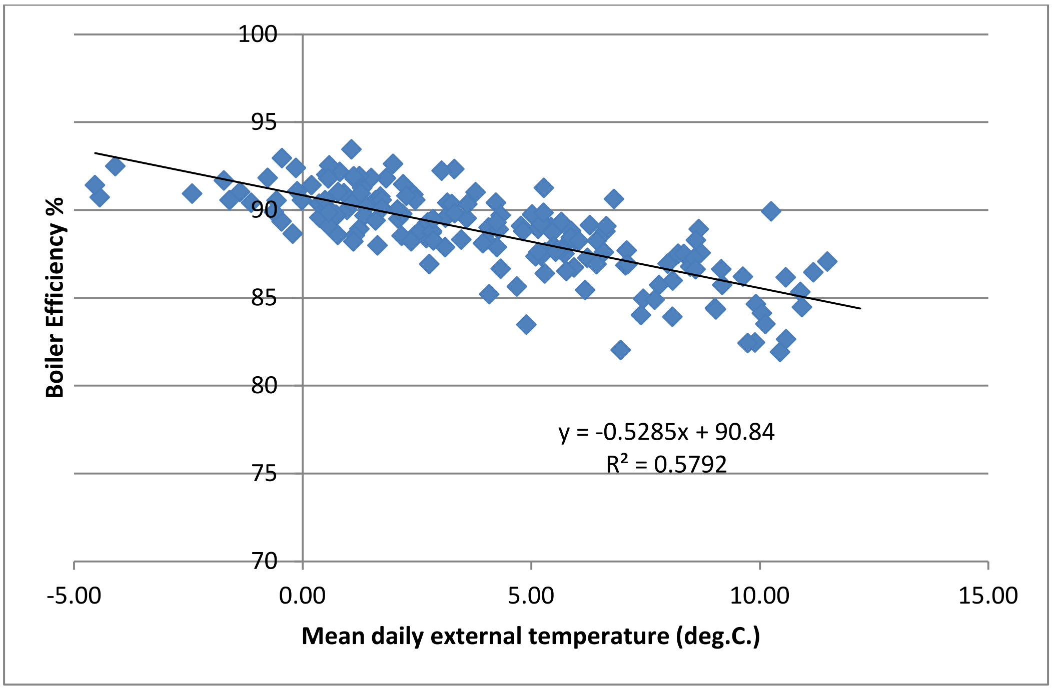


Figure 50.House B: Boiler efficiency vs mean external temperature.

Figure 51 shows that for House B there is also some pre-warming of the supply air before it reaches the heat exchanger, as it moves through the fabric of the building. There is an inverse relationship between heat exchanger efficiency and the difference between internal and external temperature as expected (Figure 52).

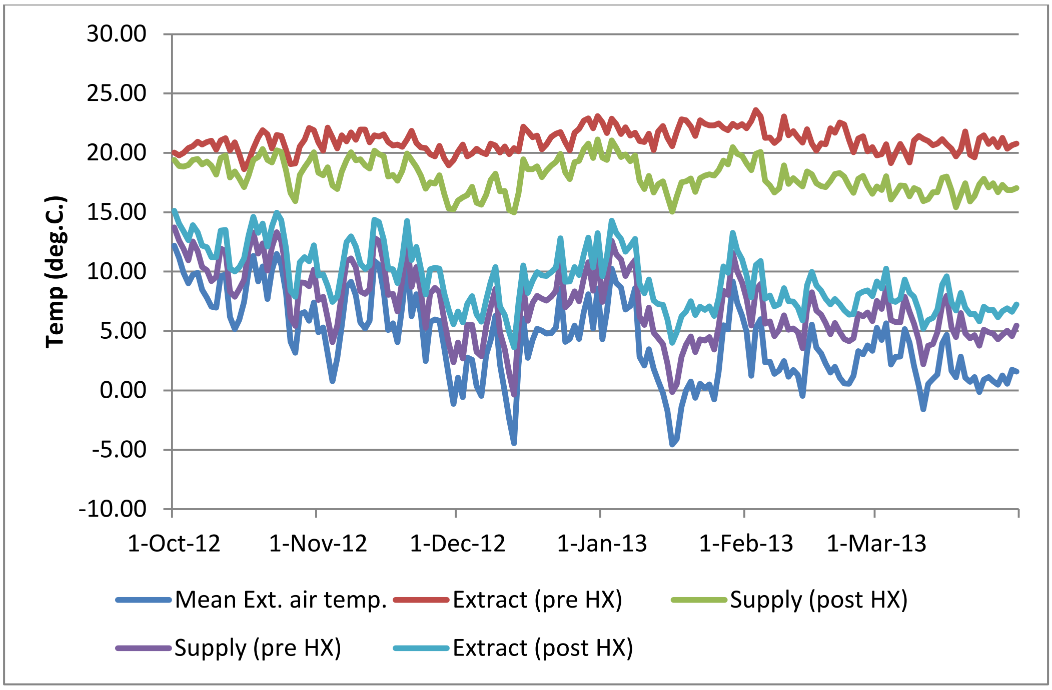


Figure 51.House B: MVHR duct measurements.

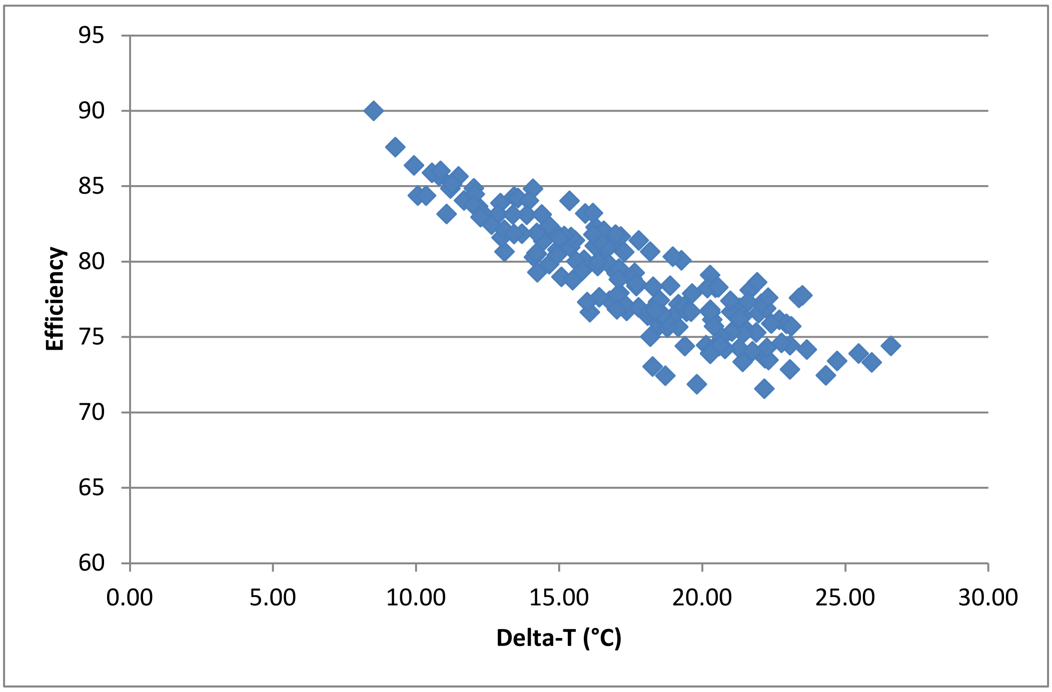


Figure 52.House B: MVHR heat exchanger efficiency.

Difficulties were experienced throughout the monitoring period with the PV DC output meter. This meter was thought to be working, but with low precision. This led to calculated conversion efficiencies which were frequently above 100% which is clearly incorrect. For this reason, the PV system for House B has not been characterised in detail. However, it was possible to plot the mean daily solar insolation vs the AC power output of the system (Figure

53). Figure 53 gives a PV system efficiency of just over 11%, which is very similar to the equivalent for House A (11.9%).

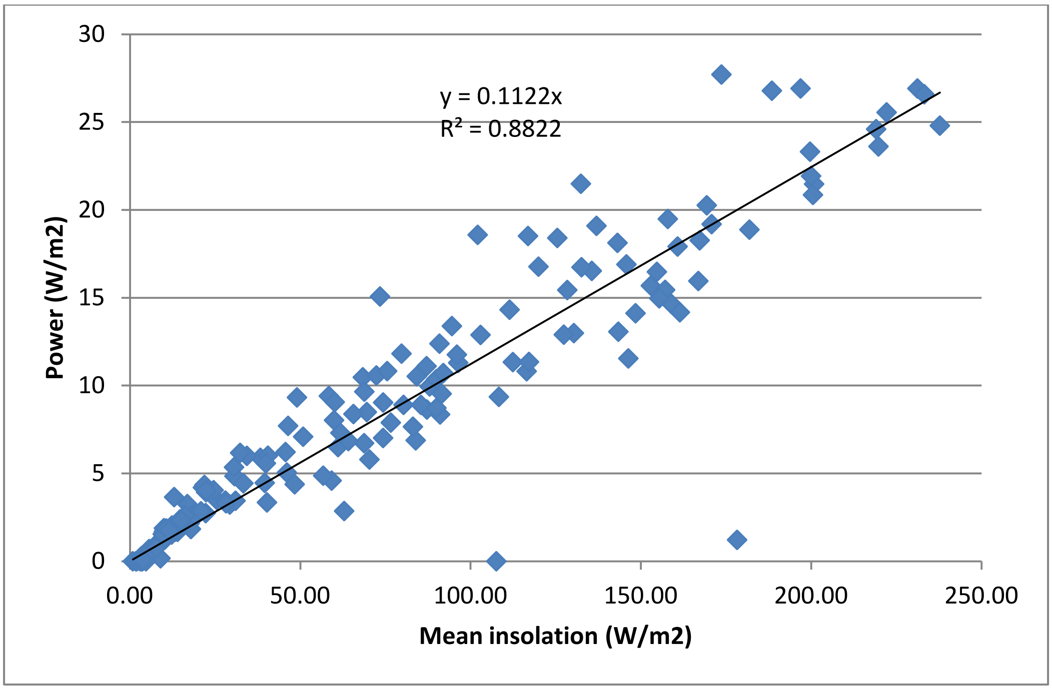


Figure 53.House B:PV system efficiency – including inverter loss.

3.7 Indoor environmental conditions

Monitoring entailed collecting environmental data for both dwellings over a six month period. Transmitters were positioned in each of the main living areas. CO_2 data has not been presented as the occupants of House B repeatedly unplugged the CO_2 sensors, and the levels in House A remained at background levels due to it being unoccupied. The following graphs display the range between the mean daily high and mean daily low temperature and relative humidity for each month. Detailed discussion of environmental data is not possible due to the lack of occupant surveys – thus no real context can be provided with which to examine the data.

Environmental data has been presented for both House A and House B over the period December 2012 – May 2012 (the period of energy monitoring for House A). However, since energy monitoring for House B was undertaken during a different period (October 2012 – March 2013), environmental data for House B is presented for this later period also.

Temperatures in House A were determined by the heating system which had been pre-set, whilst the heating system in House B could be adjusted by the householder.

Observed temperatures were stable in both House A and B when the heating system was in operation. The heating was turned on in House A on the 11th January which explains the mid-temperature between the unheated and heated periods.

Temperature and relative humidity values in the heated dwellings are in the optimum range suggested by ASHRAE for human comfort and health (ASHRAE, 2009). The master bedroom exceeded the comfort threshold in both the occupied and unoccupied dwellings, seen in Table 8.

Table 8. House A & B: Overheating and comfort summary for living room and master bedroom

		Time exceeding overheating threshold (25°C Bedroom, 28°C Living room)	*Time exceeding comfort threshold (23°C Bedroom, 26°C Living room)*
House A	*Master bedroom*	5.0%	8.2%
	Living room	0.0%	0.1%
House B	*Master bedroom*	0.1%	9.7%
	Living room	0.0%	0.0%

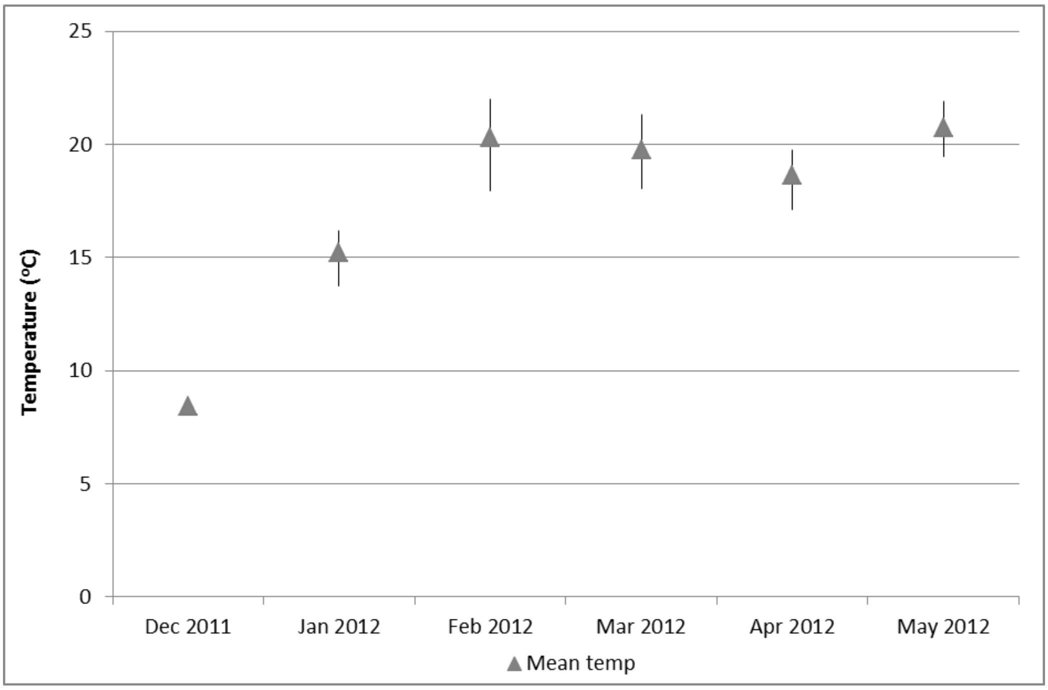


Figure 54. House A: Internal temperature – Living room

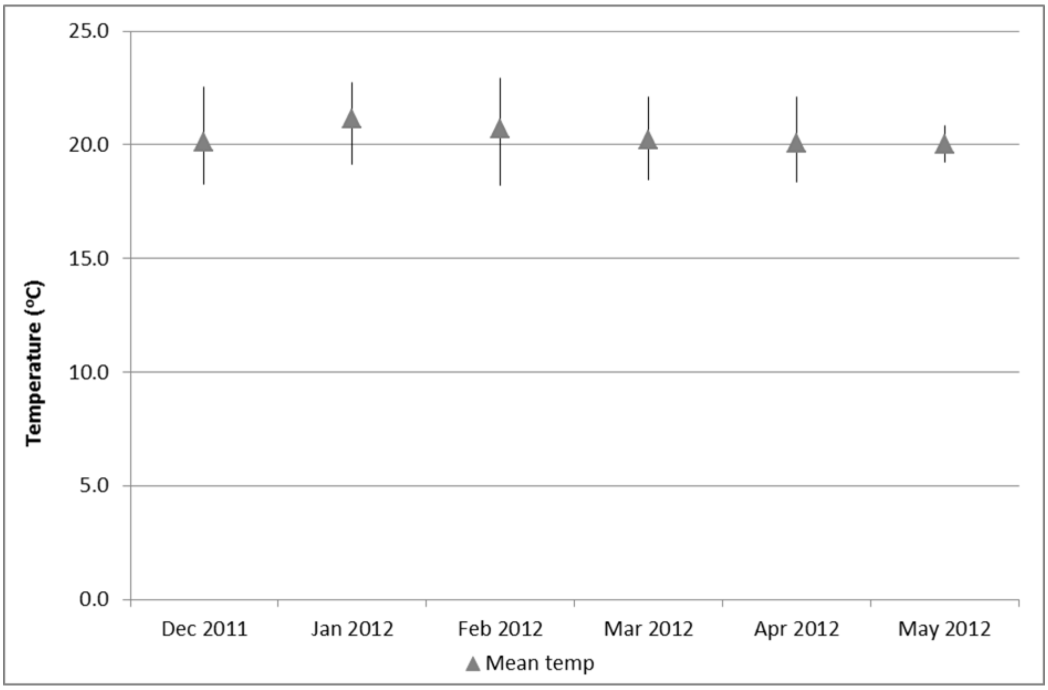


Figure 55. House B: Internal temperature – Living room

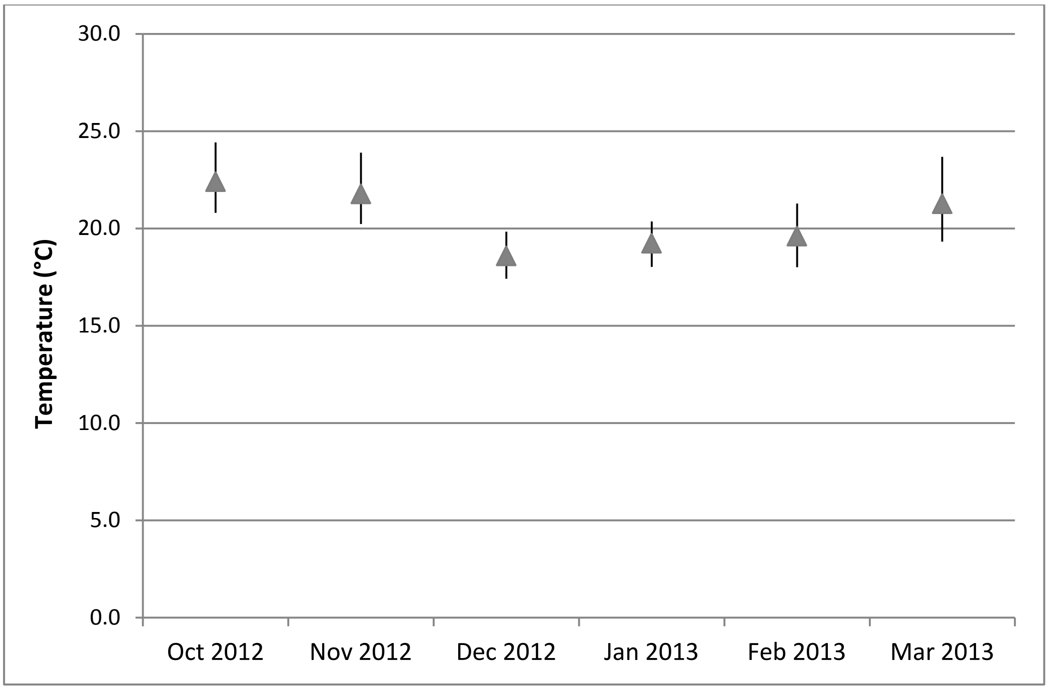


Figure 56. House B: Internal temperature – Living room.

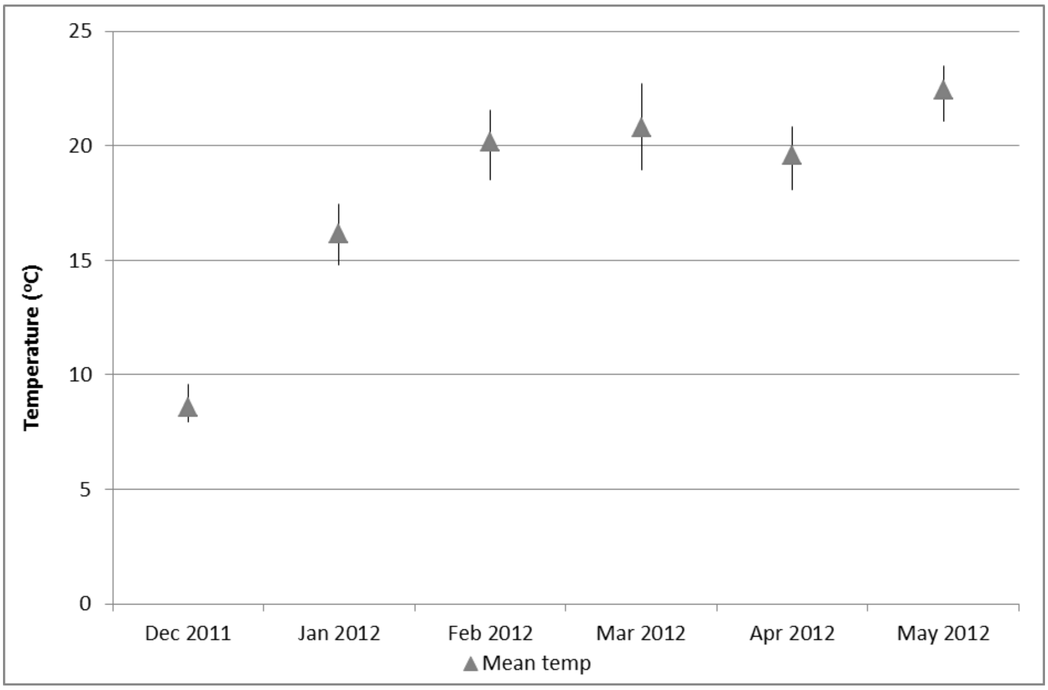


Figure 57. House A: Internal temperature – Master bedroom

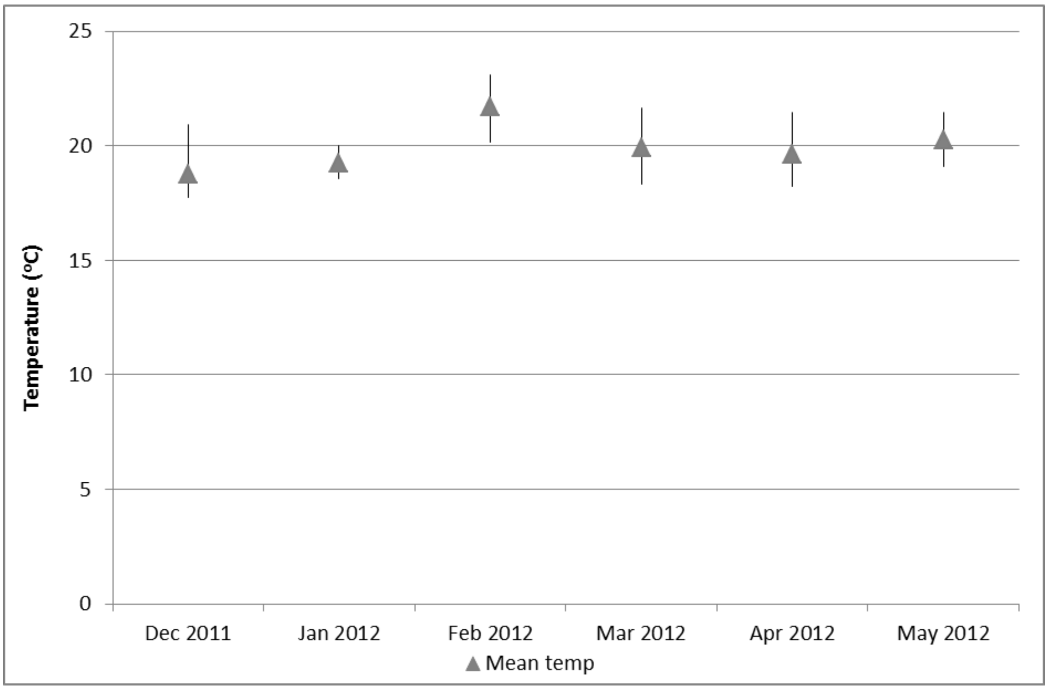


Figure 58. House B: Internal temperature – Master bedroom

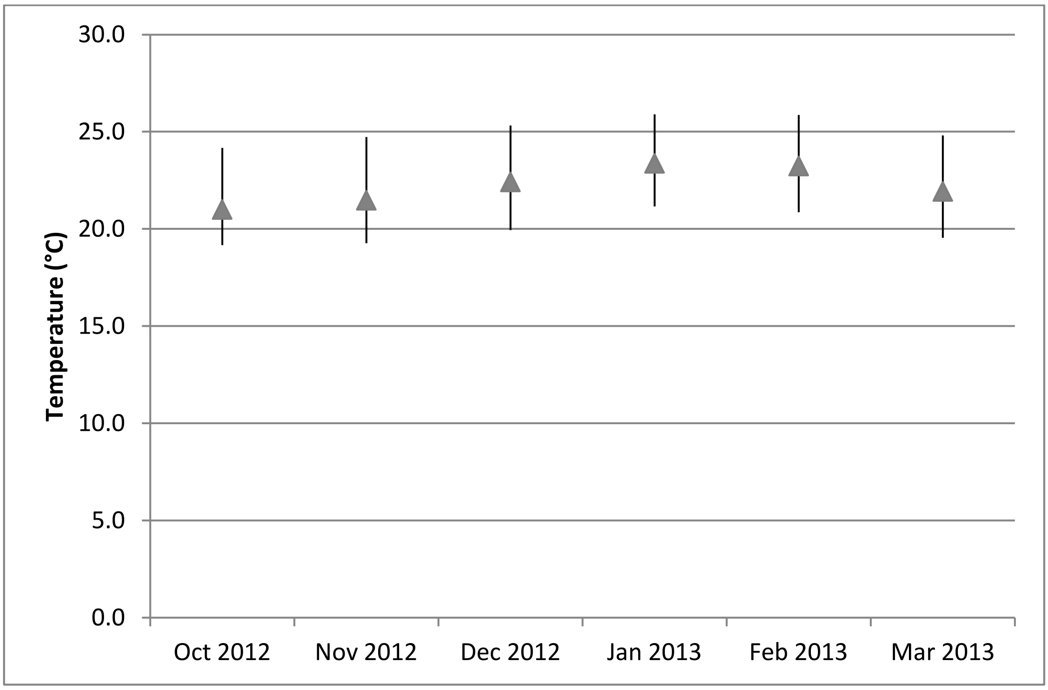


Figure 59. House B: Internal temperature – Master bedroom.

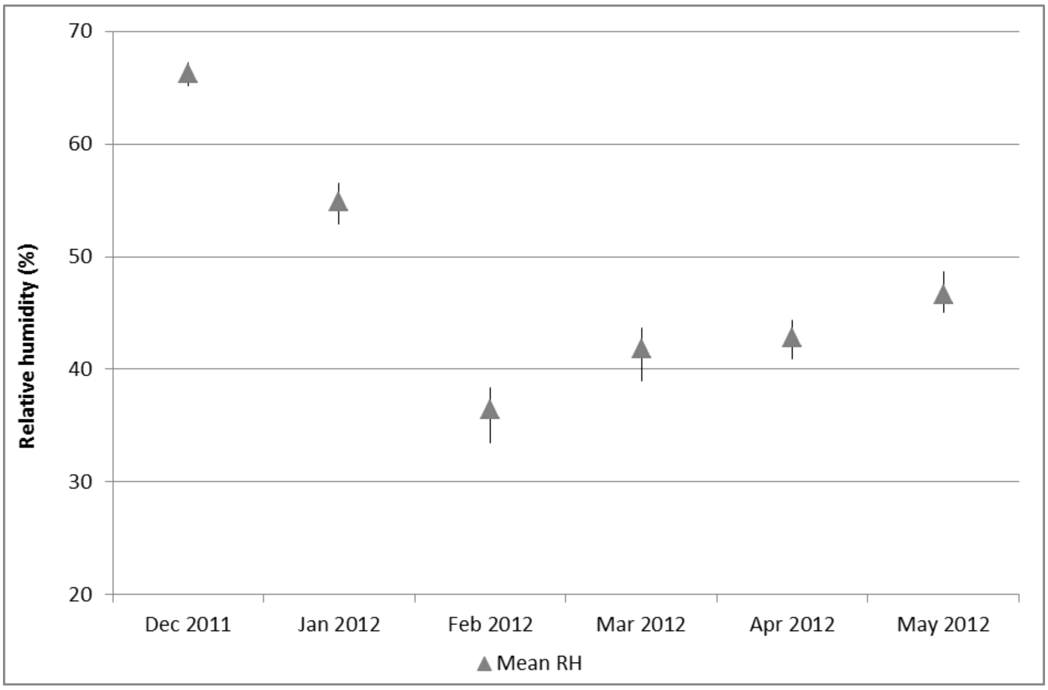


Figure 60. House A: Internal relative humidity – Living room

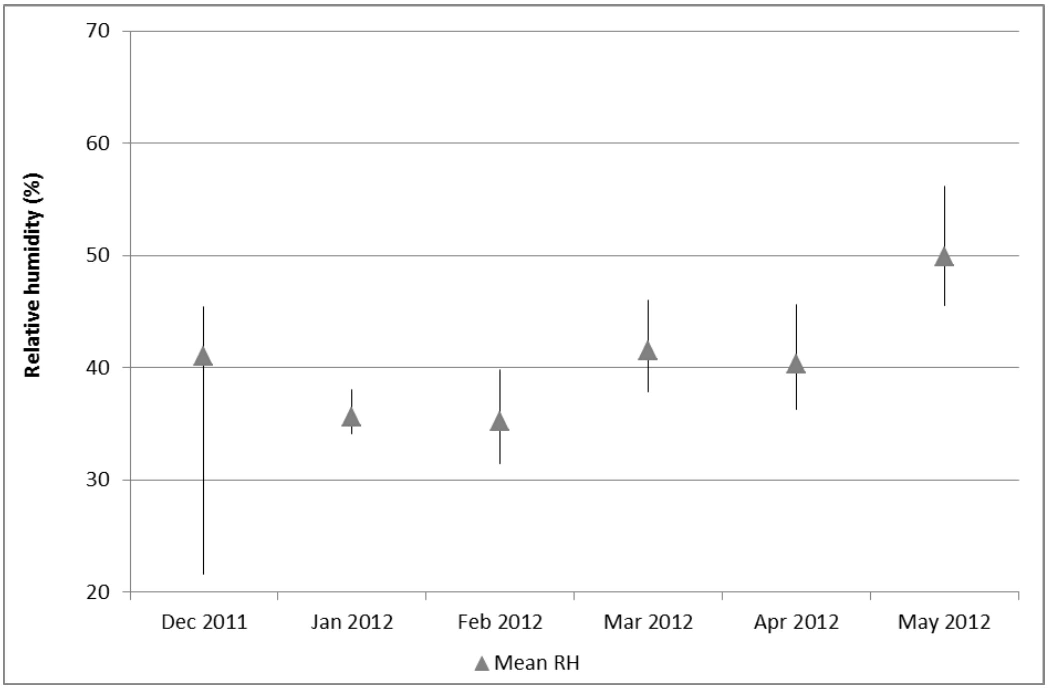


Figure 61. House B: Internal relative humidity – Living room

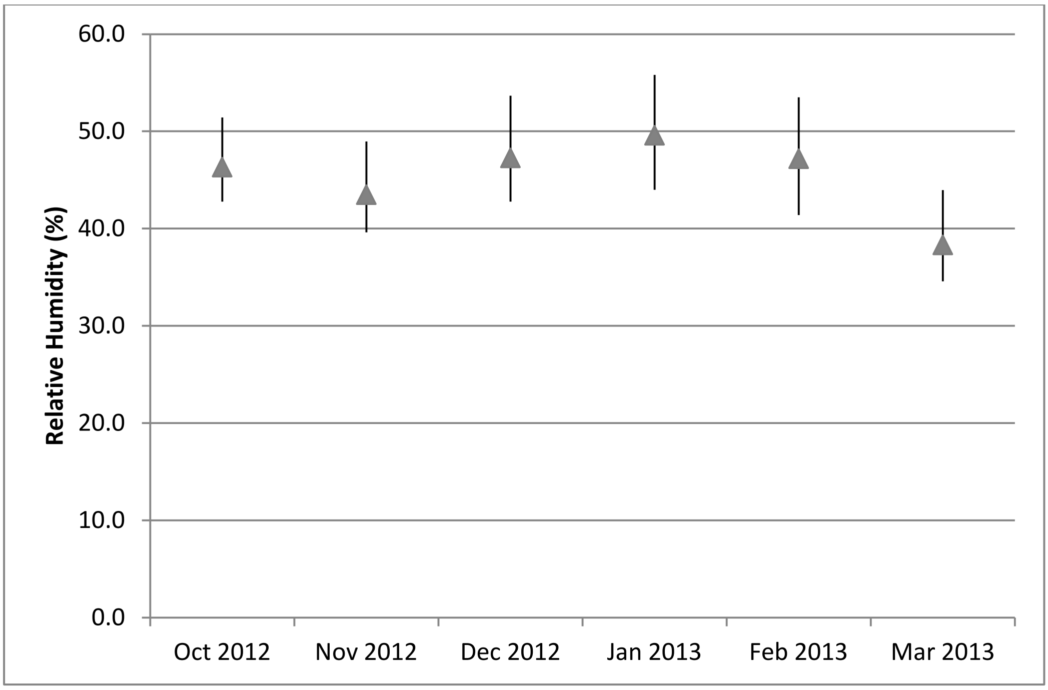


Figure 62. House B: Internal relative humidity – Living room.

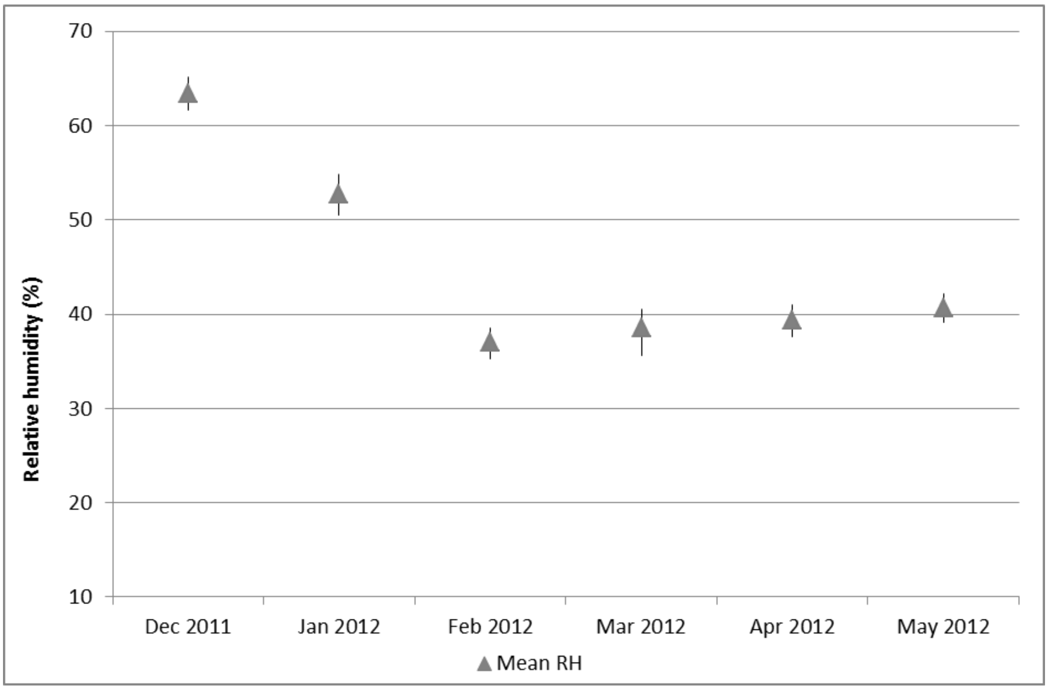


Figure 63. House A: Internal relative humidity – Master bedroom

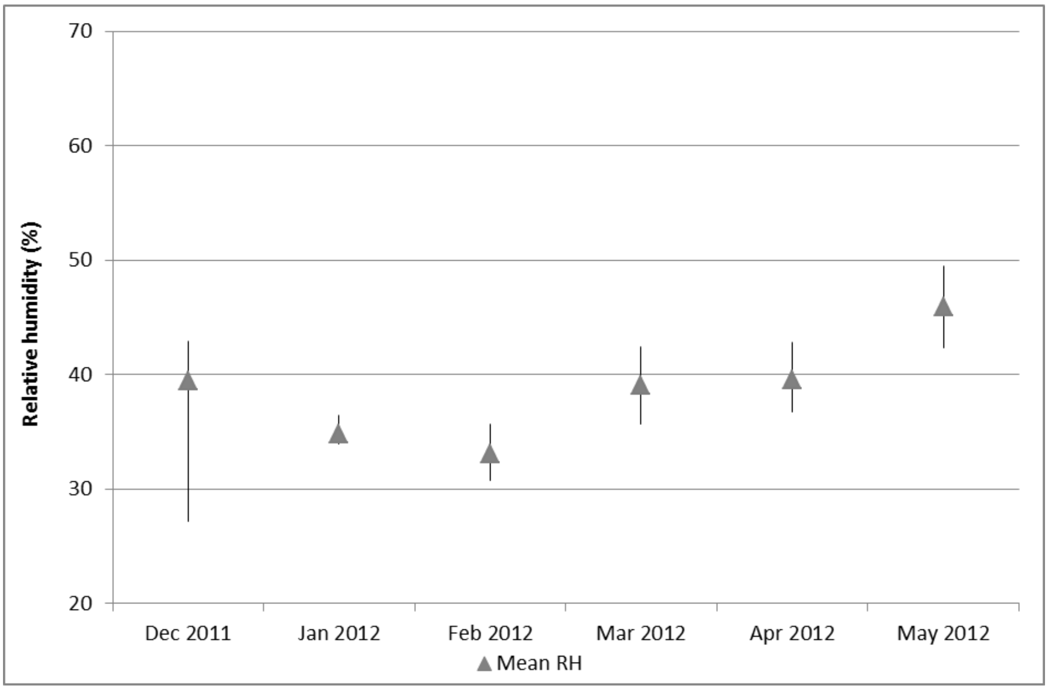


Figure 64. House B: Internal relative humidity – Master bedroom

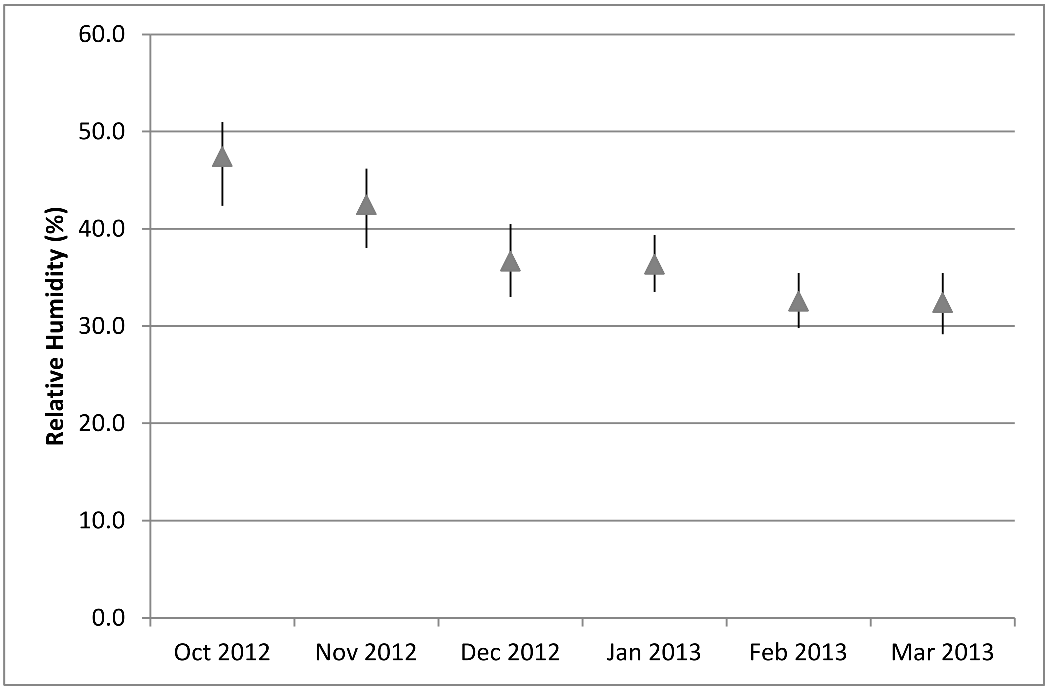


Figure 65. House B: Internal relative humidity – Master bedroom.

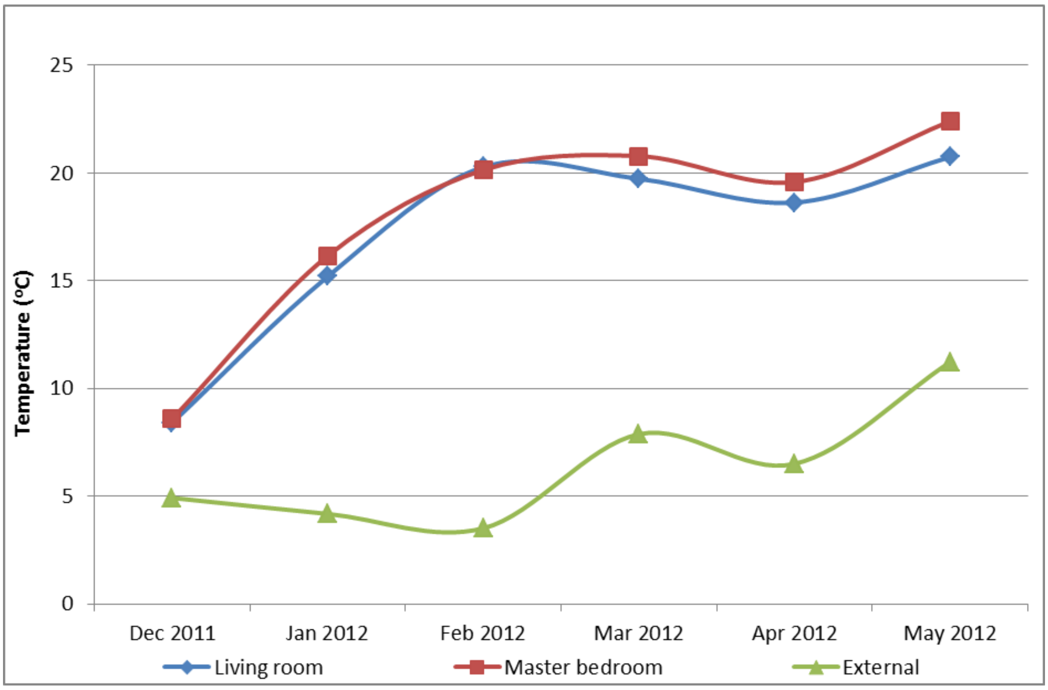


Figure 66. House A: Mean internal and external temperatures

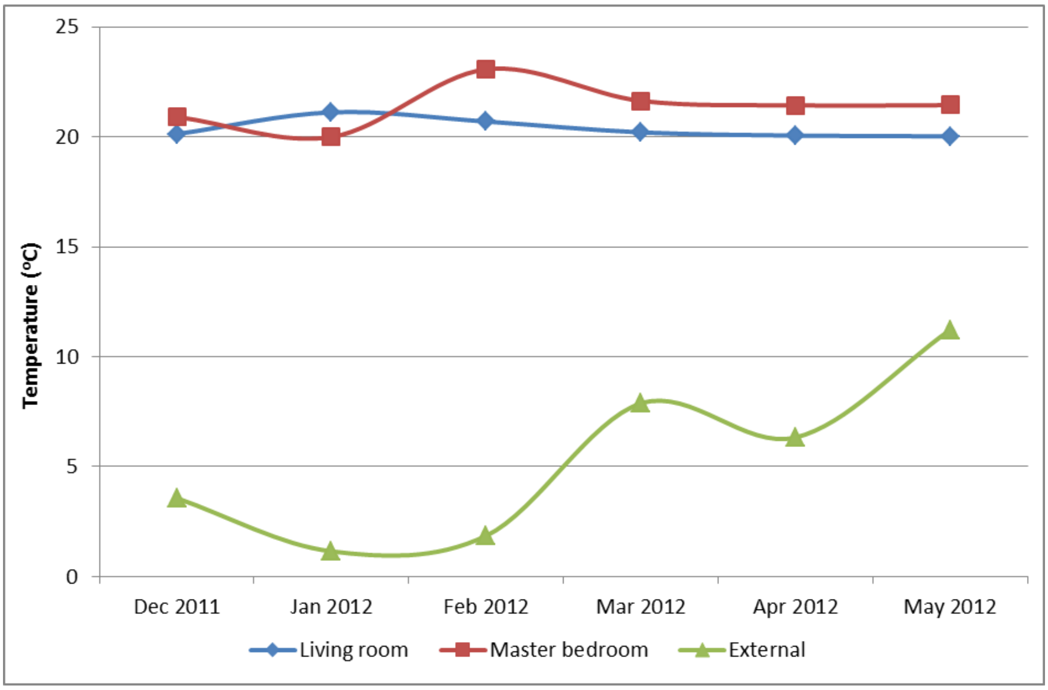


Figure 67. House B: Mean internal and external temperatures

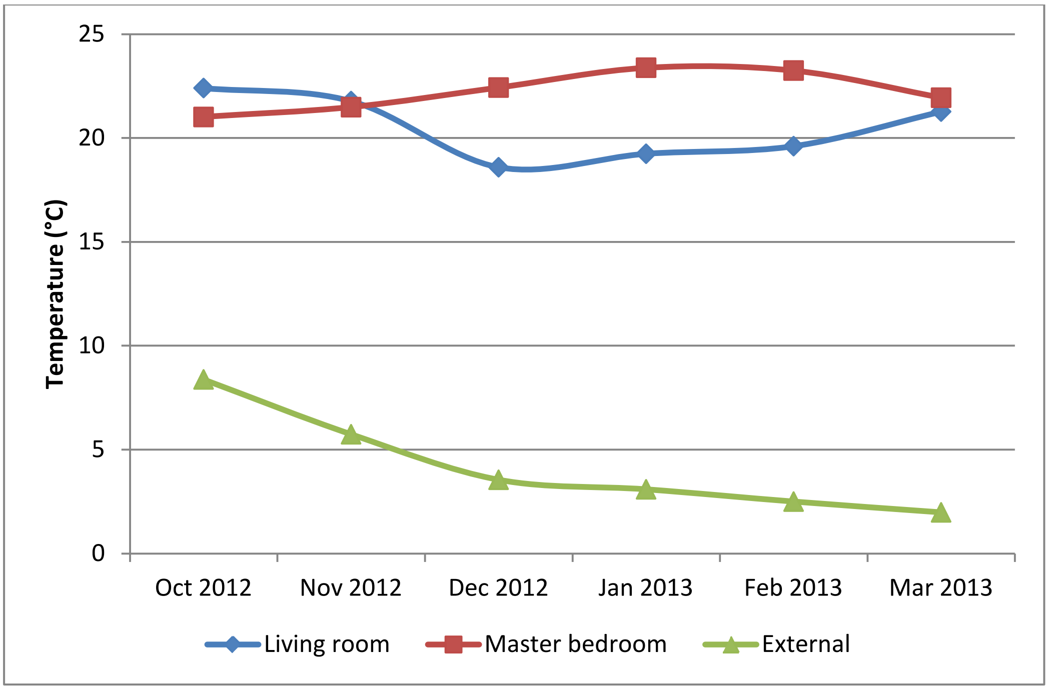


Figure 68. House B: Mean internal and external temperatures.

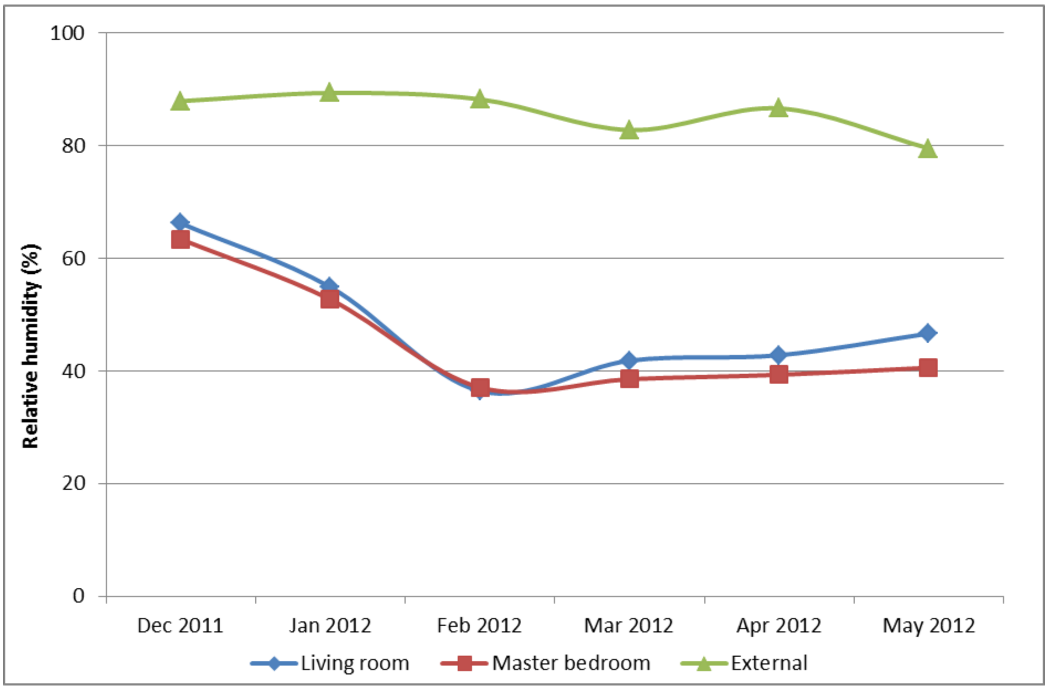


Figure 69. House A: Mean internal and external relative humidity

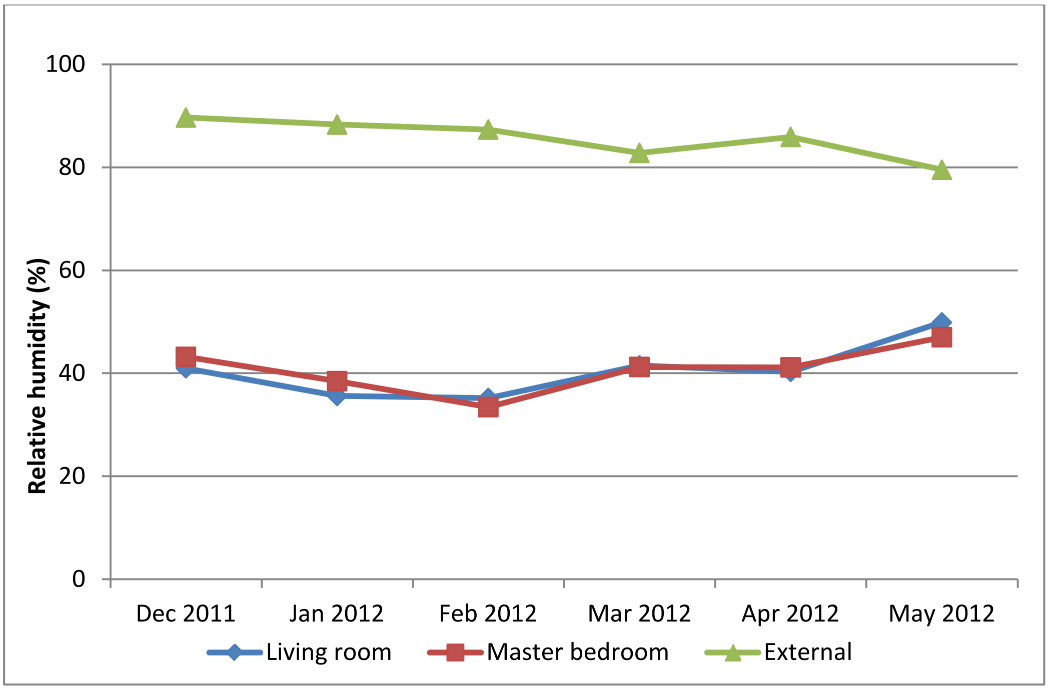


Figure 70. House B: Mean internal and external relative humidity

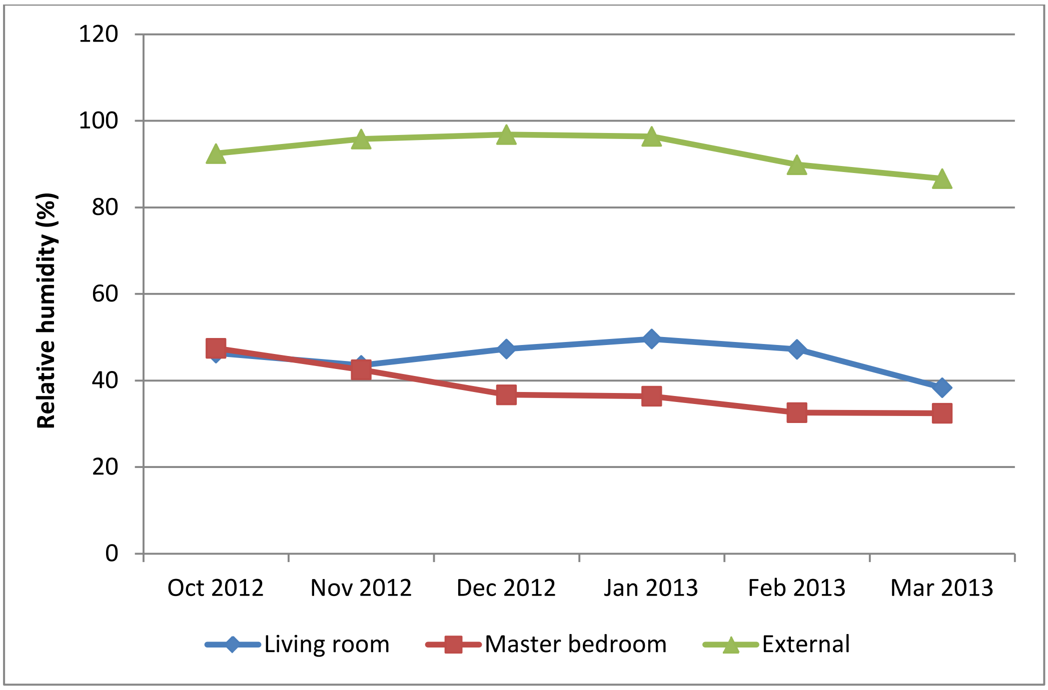


Figure 71. House B: Mean internal and external relative humidity.

4 Conclusions and Recommendations

4.1 Key findings

- Monitoring of the systems revealed the complex interactions between system performance and environmental conditions. As the temperature difference between the exterior and interior increases, boiler efficiency rises, however this in turn results in a reduction in the efficiency of the MVHR heat exchanger. Higher solar insolation (often corresponding with temperature increases) lowers PV panel efficiency; however the corresponding increase in DC output results in greater inverter efficiency.
- From the limited inferences that are be able to drawn from the SAP comparison, it would appear that calculated assumptions that exclude occupant behaviour (PV generation) are likely to be closer to what is measured in reality.
- Master bedroom mean temperature was frequently above than that of the living room in each dwelling and more prone to exceeding overheating thresholds; this could be a result of the south facing balcony glazing maximising solar gain in the bedroom, whereas the sunspace adjacent to the living room served as a thermal buffer.
- Mean internal temperatures in the occupied dwelling (House B) were more consistent throughout the monitoring period than unoccupied dwelling (House A) during the heating period (February – May), this could be the result of occupant intervention to maintain comfort levels.
- Monitoring over the additional period for House B has enabled the comparison of the dwellings. The main finding is the significant difference between the electrical appliance usage of the two dwellings. House B has very high consumption, in the top quartile of UK consumption. The reasons for this very high usage is not known, but from observations undertaken during visits to the dwelling, it appears that it may be attributable to the very high number of appliances that are plugged-in and left on standby in the living room.
- There have been difficulties setting up the monitoring equipment in the test houses, however, useful data is now being collected. It is anticipated that in future that more significant findings will arise from the data.

4.2 New technologies

- MVHR system commissioning issues would not have been noticed if not for the presence of the research team, this could have resulted in serious indoor air quality issues.
- Environmental conditions appear typical and are not expected to present any problems to the householder. But it appears that the summer bypass has not been activated on either MVHR system; this may have presented issues if higher summer temperatures were observed.
- System energy demands and renewable energy generation appear to be similar for each dwelling based on the limited data available. The photovoltaic system provided sufficient energy to power the baseload demand of the dwellings integral systems.

4.3 Areas for future work

- The considerable energy consumption associated with appliances in House B highlights the importance of affecting change in household behaviour. Improving fabric and systems performance of the house will be of limited benefit if appliance use within the dwelling is very high. The causes of such high consumption in House B have not been fully investigated. It is expected that the BUS completed questionnaire and householder interview will help.
- Dwellings are increasingly being specified with systems to reduce energy consumption (MVHR, heat pumps, Building Management Systems). These systems are frequently associated with their own energy consumption. House A generated sufficient energy from the PV array to meet the baseload demand of these systems. Twelve month in-use data from occupied dwellings will enable conclusions to be drawn as to the potential for renewable energy generation to meet the additional demands placed on these systems from occupants.
- The MVHR duct flow measurement results undertaken by the research team indicate that there are discrepancies between what has been measured by the research team and the data contained within the commissioning certificates. This may suggest that such systems are not being correctly commissioned.

5 References

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