Comparative testing of a gas absorption heat pump on the dynamic test rig


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Executive Summary

The performance of gas absorption heat pumps has been compared to the more established technologies of air source heat pumps and conventional condensing boilers for the purposes of space heating.

This test programme used Kiwa's unique Dynamic Heat Load Test Rig. This rig combines testing of real hardware in a software simulation loop, which provides realistic and reproducible heating loads over a period of 24 hours, allowing different heating technologies to easily be compared.

Three technologies were compared – a gas absorption heat pump (GAHP), an electric air source heat pump (ASHP) and a combination condensing gas boiler. Two simulated houses were used as the test basis: one with average UK heat demand and one with a substantial heat demand, representing a very large property.

The results indicate that the daily energy consumption of a property strongly depends upon:

- The ability of the system to operate bimodally or unimodally whilst giving acceptable internal temperatures. This is a function of appliance operating temperature, and kW output rating at this temperature.
    - Bimodal – heating pattern where the heating appliance is enabled twice a day: between 07:00 to 09:00 and 16:00 to 23:00. This is as per SAP and is used in the dynamic test rig program.
    - Unimodal – heating appliance is enabled for one period a day from 07:00 - 23:00.
    - Continuous – heating appliance is enabled for 24 hours a day.
- External temperature
- System water temperature (especially return)
- The instantaneous and average efficiency of the appliance

Primary fuel use (assuming electricity is supplied from a combined cycle gas turbine* with an efficiency of 47.7%[1]) is a strong function of both electric and gas usage of the device, not just the gas.

Beyond this the work demonstrates the sheer complexity of trying to compare the heat required, the gas plus electricity used and primary energy equivalence of both small and large houses. Different heating patterns with different appliances and different heat emitter temperatures will markedly affect both the reported efficiency and the actual energy used. A somewhat higher efficiency for the appliance may not save primary energy, if the technology used to obtain the high efficiency results in the building remaining at a higher average temperature and thus using more primary energy.

The following tables compare total carbon emissions to maintain a property at the declared average internal temperatures (shown in brackets) when the external temperatures are $0^{o}C$

and 7ºC . For comparison UK field trials show average internal temperatures in the range 17.7ºC [2].

	Daily carbon emissions ($kgCO_2e$/day) (Average internal temperature (°C))			
	Small house (300W/K)		Large house (700W/K)	
External temp 0ºC	**Boiler**	**ASHP**	**Boiler**	**GAHP**
Bimodal Rads 60ºC	N/T	N/T	N/T	N/T
Bimodal Rads 45ºC	N/T	N/T	N/T	N/T
Unimodal Rads 60ºC	27.5 (19.0)	29.0 (17.7)	61.7 (18.5)	60.6 (18.4)
Unimodal Rads 45ºC	26.9 (18.9)	N/T	N/T	N/T
Continuous Rads 60ºC	N/T	34.2 (20.8)	N/T	N/T
Continuous Rads 45ºC	30.5 (20.9)	30.5 (20.8)	65.0 (20.9)	63.1 (20.8)
External temp 7ºC	**Boiler**	**ASHP**	**Boiler**	**GAHP**
Bimodal Rads 60ºC	17.9 (18.8)	N/T	37.5 (18.2)	37.1 (18.2)
Bimodal Rads 45ºC	N/T	N/T	N/T	N/T
Unimodal Rads 60ºC	20.0 (20.3)	17.4 (19.5)	N/T	N/T
Unimodal Rads 45ºC	19.4 (20.0)	N/T	42.4 (19.8)	40.2 (19.8)
Continuous Rads 60ºC	N/T	19.3 (20.9)	N/T	N/T
Continuous Rads 45ºC	N/T	16.4 (20.9)	N/T	N/T

Key: N/T = Not tested as would not be realistic of operation of the appliance in the field. Reasons for this may include: there would be insufficient heat output from the appliance to meet the heat demand of the house, the radiators would be too small to deliver sufficient energy to the house, or the appliance would cycle too frequently.

The equivalent CO_2 emissions were calculated, assuming emissions factors of 0.5173 $kgCO_2e$/kWh for electricity and 0.1841 $kgCO_2e$/kWh for gas[3]. The ASHP could not achieve the 60°C radiator temperatures. More detailed notes are given in the results.

As expected, for the larger property the GAHP has lower carbon emissions than the gas boiler, and in the smaller property the ASHP and gas boiler are finely balanced. It is this complication of heating operating mode (i.e. bimodal, unimodal or continuous) and seasonal variation in heat demand as produced by mCHP that caused the introduction within SAP of PAS 67[4]. This tests appliance performance at 10, 30 and 100% of output and then integrates over the year. It can be argued a similar technique should be applied to heat pumps.

Some generalisations are possible:

- A bimodal heating pattern saves energy over unimodal heating, and unimodal heating saves energy over continuous heating, however the internal temperature achieved may not be sufficient (at all external temperatures) when using bimodal heating. Unfortunately there is an element of personal preference in this, but it should be made clear to householders that (where it is technically possible) bimodal heating does reduce daily energy consumption and thus energy consumption, irrespective of energy source.

- Lower temperature emitters (or more correctly emitters with low water return temperatures) reduce fuel use.

- Mixing electricity and gas energy consumptions is complex unless reference is made to primary energy. Thus quoting the efficiency of a GAHP (which has a significant electrical consumption) just on gas input energy does not provide a realistic reference point compared with (for example) a gas boiler (which has a very small electrical consumption). It is often useful to use emissions of carbon dioxide as a proxy for primary energy.

In the case of the smaller house, the balance of carbon emissions between the gas boiler and the ASHP becomes fine with the ASHP showing an advantage at 7°C, and the gas boiler an advantage at 0°C. However both are dependent upon radiator temperature – with radiators designed at 45°C (i.e. an 3.1 oversize factor on their normal rating) and an external temperature of 7°C, the ASHP carbon saving does become more significant – up to 15%.

Compared with ASHPs, GAHPs have the advantage of being able to deliver heat in large quantities and at higher temperatures, which may allow then to be retrofitted in existing installations with fewer modifications to the property. However, truly domestic scale GAHPs are still in development. The unit tested here was really suitable for very large domestic or commercial applications.

* This assumes that all the electricity consumed is generated by combined cycle gas turbine which is the most efficient type of fossil fuel power station. With the current mix of coal generation in the UK, the primary energy consumption of the ASHP (and also the GAHP), will be higher.

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1 Introduction

Recent government programmes have concentrated on investigations of the performance of electric air source heat pumps. However, the domestic scale gas-fired heat pump has arrived on the continent in the past few of years, and these appliances appear to offer promising performance. There are two types:

- The absorption process, which is currently marketed by Robur, Buderus and Potterton. These are air source units (which are essentially badged versions of the same product) which use the ammonia water absorption pair and have claimed efficiencies of up to 148% (on a gross CV basis)[5]. A reasonable output rating in the UK climate is about 28kW i.e. similar to a modern combi gas boiler, however the units currently on sale have outputs of 36kW and are targeted at commercial applications.

- The adsorption process, which is currently marketed by Vaillant and Viessmann. These are ground or solar assisted water sourced units which use the heat of adsorption of a refrigerant onto a solid (water/zeolite pair). They currently have outputs of less than 10kW. A more refined air source version of this product (ammonia/carbon pair) is currently being developed by the Warwick University spin off company, Sorption Energy. They claim efficiencies of approaching 140%[6].

The main advantage of gas-fired heat pumps is the improvement in thermal efficiency whilst using essentially the same infrastructure as an existing gas boiler. The electricity supply requires no upgrade and the existing gas supply pipeline only has to be relocated to outside. Such gas units might play a major part in the UK's carbon reduction strategy in the model proposed by National Grid[7]. They should also be capable of operating on biogas and/or hydrogen.

At this time there have been few tests undertaken on gas-fired heat pumps in the UK, and they are currently only sold to the commercial market, rather than the domestic market. So it was thought prudent to begin UK testing of the gas-fired heat pump in comparison to other heating appliances.

The dynamic heat load test rig developed by Kiwa is recognised as being a reliable, reproducible and low cost alternative to early stage field trials. This has been used in this test program to give real information on the current leading EU gas absorption heat pump compared with a condensing gas boiler in a large house, a condensing gas boiler in a small house and an electric air source heat pump.

It is appreciated that this is only a snapshot of current performance; however, speaking to manufacturers, there is clearly a feeling that some interest from government (in the form of RHI) could really stimulate research and development in this market.

2 Description of test programme

Three appliances were tested under a range of conditions using simulations of suitably sized houses:

a) 28kW condensing gas combi boiler in large (700W/K) house [base case].

b) 28kW condensing gas combi boiler in small (300W/K) house [base case].

c) Gas absorption heat pump (GAHP) in the large house.

d) Electric air source heat pump (ASHP) in the small house.

External temperatures were set at 0°C and 7°C which are the same temperatures as those specified in the ASHP test standards[8]. Radiator temperature is an important variable in the use of heat pumps so flow temperatures of 60°C and 45°C were used for all four appliances (where possible). The radiators were appropriately sized for the different flow temperatures, ie larger radiator areas were used at the lower flow temperature and vice versa.

Different heating patterns were used for each flow temperature and ambient temperature condition to examine cycling, start up and shut down efficiencies.

2.1 Dynamic heat loss test rig

2.1.1 Introduction

The Dynamic Heat Load Test Rig (DHLTR) has been designed to allow domestic wet central heating appliances to be evaluated in conditions that reflect ‘real-life’ usage. The rig is constructed in such a way that both the appliance and its associated controls are tested in combination, this allows for the fact that the control system and system commissioning may play a significant role in the overall efficiency of any installed system.

The rig is designed to run over a 24 hour cycle, reproducing the behaviour of the system under test within a simulated property of known thermal characteristics, but in a controlled manner. Thus experiments are similar to those done in matched pair test houses, but with a much greater degree of control over the conditions.

The tests carried out on this rig are entirely different to those done to the existing boiler / Micro-CHP / heat pump testing standards. In these tests only a relatively limited range of operation is examined. Boiler Efficiency Directive (BED) compliance tests are very short duration, with the boiler controls disconnected, and using fixed water return temperatures of 60ºC at 100% input and 30ºC at 30% input. In contrast, the dynamic nature of the tests with this rig ensures the appliance is operated in a way that would be encountered in normal use.

During the DHLTR tests, the appliance is therefore not running under stable, optimal conditions and this can lead to lower efficiencies. Previous studies indicate the difference in efficiencies between laboratory results (using testing standards) and field trial ('real world') data can be as high as 5-8%[9].

2.1.2 Rig Description

The rig is based around a wet central heating system of the Y-plan design. The bulk of the rig is two copper water cylinders. One of these is plumbed in conventionally as a domestic hot water (DHW) cylinder. The second tank contains the equivalent volume of water as the heating system being simulated. The cooling load, to represent the heat loss from the household radiators and pipework, is simulated in hardware using a plate heat exchanger. The pipework includes a range of different control systems encountered in household heating systems, such as pumps, manual bypass loops, automatic bypass loops and thermostatically controlled valves (TRV). Provision is made for control system hardware such as timers/programmers, room thermostats, outside temperature sensors and remote TRV modules. These items can be installed into up to three separate temperature controlled enclosures.

The hardware is linked using a computer program that simulates the thermal characteristics of a house and runs this simulation in real time:

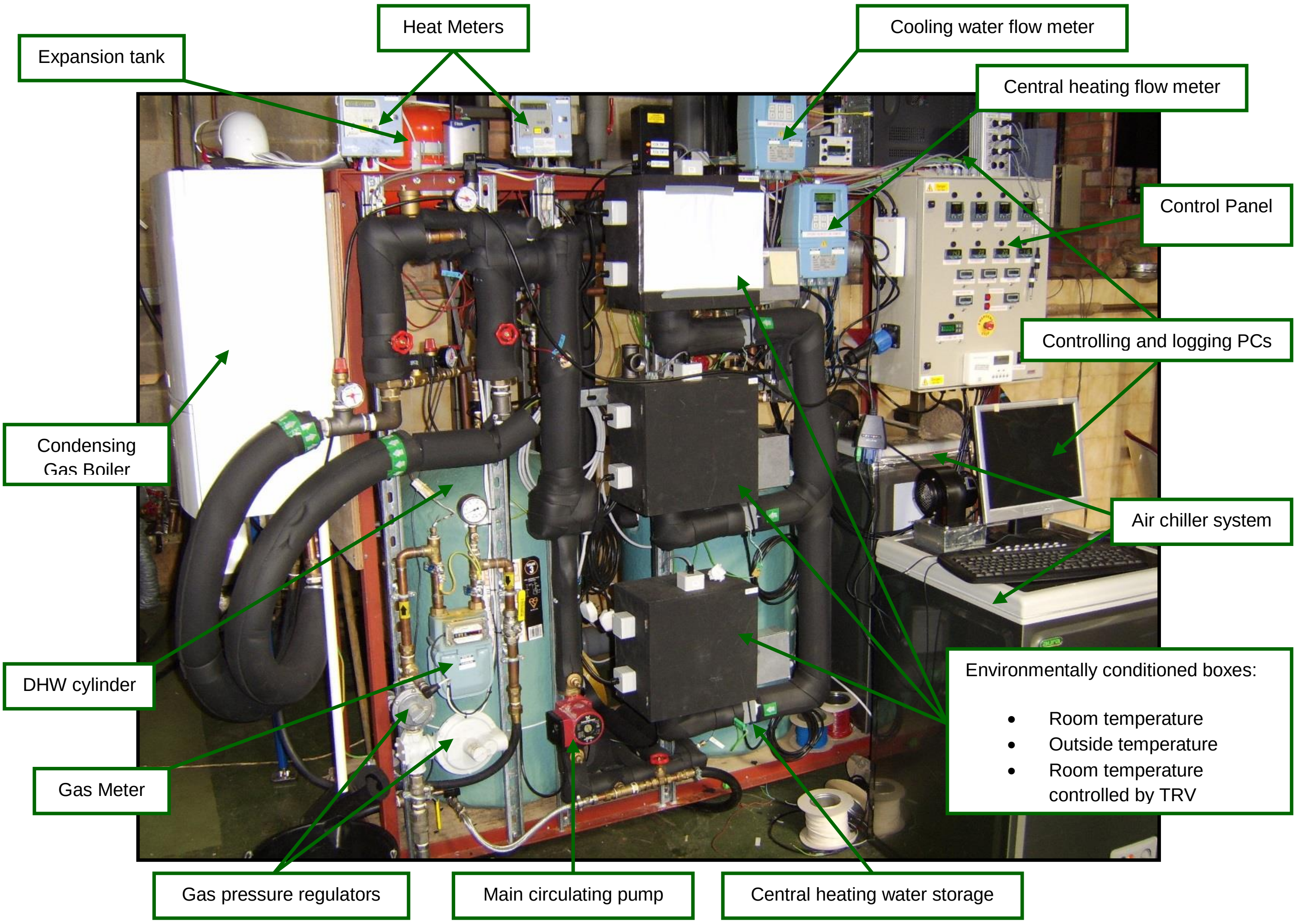
- Firstly, predicting the heat loss from the radiators and controlling this by adjusting the cooling water flow to the plate heat exchanger.
- Secondly, the program predicts the heat lost from the building fabric.
- Thirdly, by doing a heat balance over short time intervals to predict the current household average room temperature.

The room / outside temperatures are then transmitted to independent controllers that set the temperatures in the temperature controlled enclosures in which physical thermostats are located.

A hot water draw off pattern can also be programmed for a 24 hour period, simulating DHW use in a property, although this was not used in this test programme.

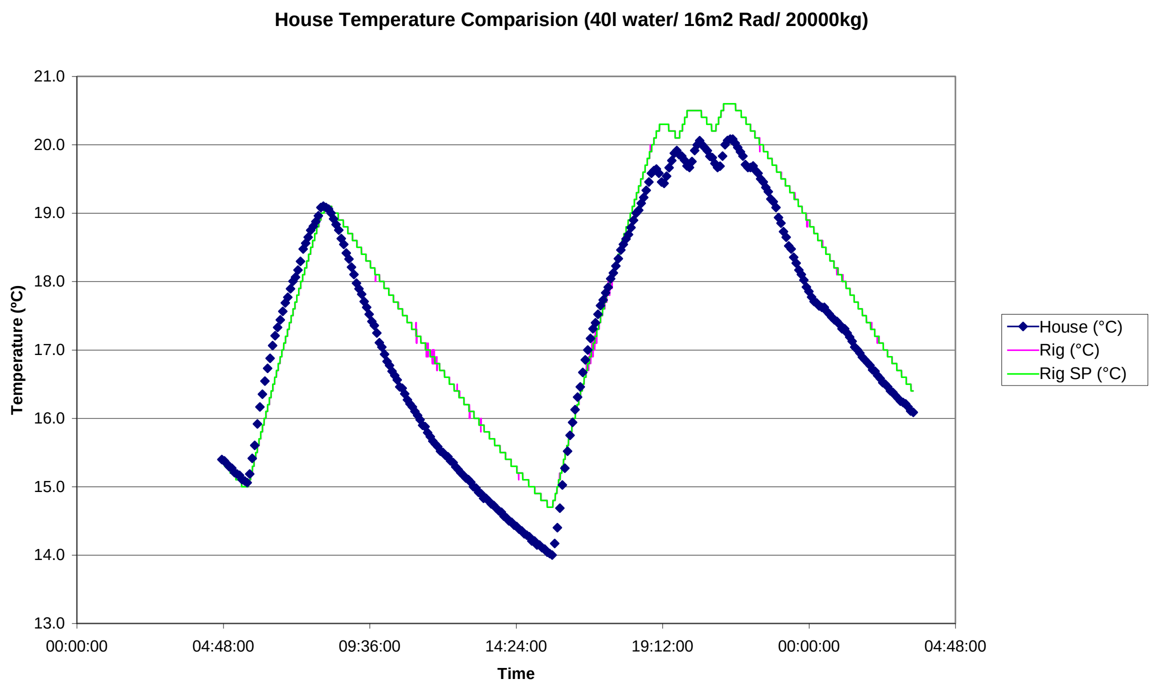
The simulation of the house is based on the heat loss coefficient of the property under scrutiny, along with an estimate of its thermal mass. Radiator area and water content were calculated using appropriate estimations for the different flow temperatures. To this, an outside temperature can be applied either as a constant value or as a profile, these tests were undertaken with constant temperatures of 0°C and 7°C.

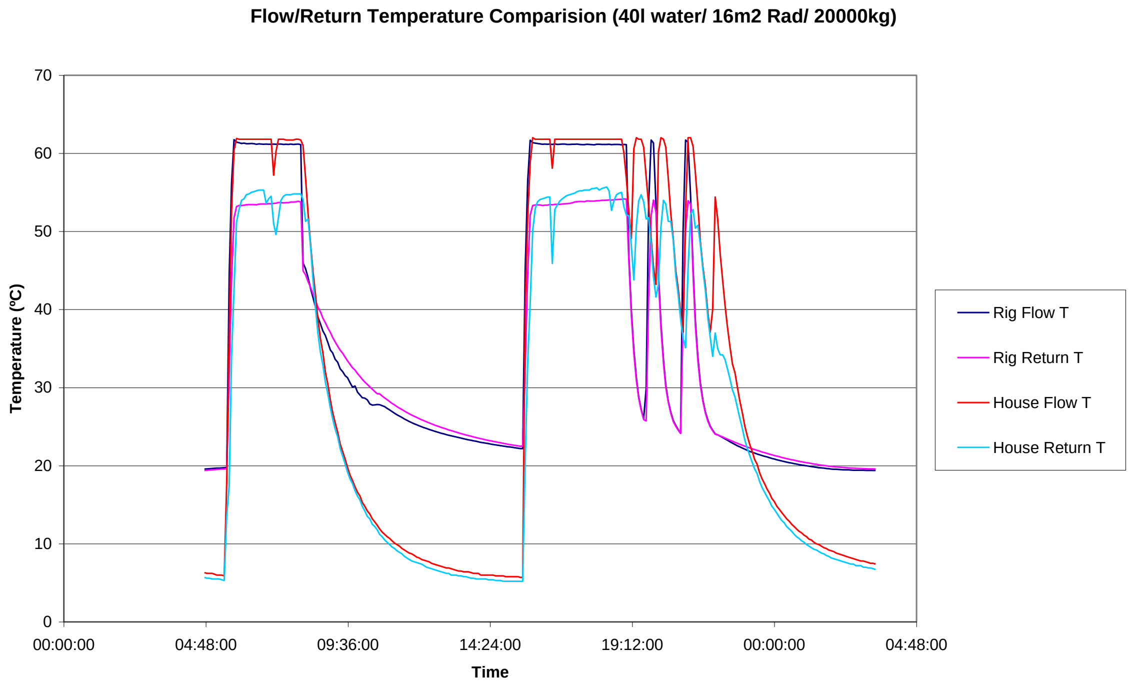
The photograph below shows the test rig itself with a condensing gas boiler installed.



The graphs below show the DHLTR test of a condensing gas boiler in a simulated 4 bed detached house, against data from the same boiler in the real property on an average winter's day, in order to demonstrate the accuracy of the simulation.

Demonstration of accuracy of DHLTR





Results are reported including pumping power which was changed throughout the test regime to achieve the desired flow rates for each test.

2.2 Detailed Test Regime

The following table details original test conditions, however during the test programme extra tests were undertaken to investigate parameters such as flow rates and heating patterns.

	House model	House heat loss coefficient	Outside Temp	Radiator area (assuming k2 rads installed)	Heating Pattern	Flow Temp	Room stat Temp	Max Heat out from rads	Heat required to heat property
		W/K	°C	m^2	realistic	°C	°C	W	W
Gas boiler 28kW	A1	700	7	12.24	bi	60	21	19591	9800
		700	0	12.24	uni	60	21	19591	14700
	A2	700	7	17.28	uni	45	21	18120	9800
		700	0	17.28	cont	45	21	18120	14700
GAHP 36kW	A1	700	7	12.24	bi	60	21	19591	9800
		700	0	12.24	uni	60	21	19591	14700
	A2	700	7	17.28	uni	45	21	18120	9800
		700	0	17.28	cont	45	21	18120	14700
Gas boiler 28kW	B1	300	7	5.76	bi	60	21	9219	4200
		300	0	5.76	uni	60	21	9219	6300
	B2	300	7	7.92	uni	45	21	8305	4200
		300	0	7.92	cont	45	21	8305	6300
ASHP 7kW	B1	300	7	5.76	uni	60	21	9219	4200
		300	0	5.76	cont	60	21	9219	6300
	B2	300	7	7.92	cont	45	21	8305	4200
		300	0	7.92	cont	45	21	8305	6300

House model	Description		Number of radiators
A1	"Large house"	e.g. 5-6 bedroom detached house, not recently insulated	17 radiators (flow T = 60°C)
A2			24 radiators (flow T = 45°C)
B1	"Small house"	e.g. 2-3 bedroom semi-detached house	8 radiators (flow T = 60°C)
B2			11 radiators (flow T = 45°C)

The set point for the room temperature was always 21°C, and different heating regimes were used to look at energy use in bimodal, unimodal and continuous heating modes:

- Bimodal – heating pattern where the heating appliance is enabled twice a day: between 07:00-09:00 and 16:00-23:00. This is as per SAP and is used in the dynamic test rig program.

- Unimodal – heating appliance is enabled for one period a day from 07:00 – 23:00.
- Continuous – heating appliance is enabled for 24 hours a day.

For 24 hour testing it is important that the start and end conditions are the same; so to keep the offset between the temperature of the property at the beginning and end to a minimum, the starting temperature of the house was varied for each test. Calculations were performed to find the optimum start temperature. The dynamic test rig was then left to operate in the desired heating pattern for 24 hours.

The large house was a typical large and/or poorly insulated house that would use between 32,000 to 38,000kWh/y of heat depending upon the DHW demand. The small house is a semi-detached moderately insulated house that might use 14,000 to 16,000kWh/y of heat depending upon DHW demand. The gas boiler was sized at 28kW to provide a satisfactory flow of instantaneous DHW for a shower.

2.3 Appliance Specifications

The following table shows, for the appliances under test, the manufacturers' declared thermal outputs and COP/efficiencies at specific external temperatures and flow temperatures (shown in the table as A+7W50 = external air temperature of +7°C and water flow temperature of 50°C). The gas boiler was a combi boiler. Boilers are tested according to BED.

		Efficiency (%)	Thermal Power (kW)
Gas boiler	condensing mode	91.1*	30.3
	non-condensing mode	N/A	28
	DHW mode	N/A	33
GAHP	A+7W50	152	35.4
	A+7W65	119	27.5
	A-7W50	125	31.5
	nominal output	N/A	25.7
ASHP	A+2W35	317	8.5
	A+7W35	418	9.0

*This is the declared SEDBUK efficiency

3 Results

Efficiency is calculated throughout this report using the following equations:

- Efficiency of appliance = heat out from appliance / (gas in + electric in)
  (this is equivalent to the instantaneous efficiency or COP averaged over 24 hours)

- Efficiency of system = heat out from radiators / (gas in + electric in)
  (this is equivalent to the system efficiency or SPF_{H4}, assuming no buffer tanks or DHW use)

The electrical input includes all the pumps to reach the stated flow rate, the gas boiler has a pump within the appliance box, however the other appliances require additional pumps which run continuously no matter what the heating pattern. This will downgrade their efficiency by 4-10% (see Section 4.1).

3.1 Gas boiler in Large House (700W/K)

Table 1: Results from gas boiler in the large house (700W/K)

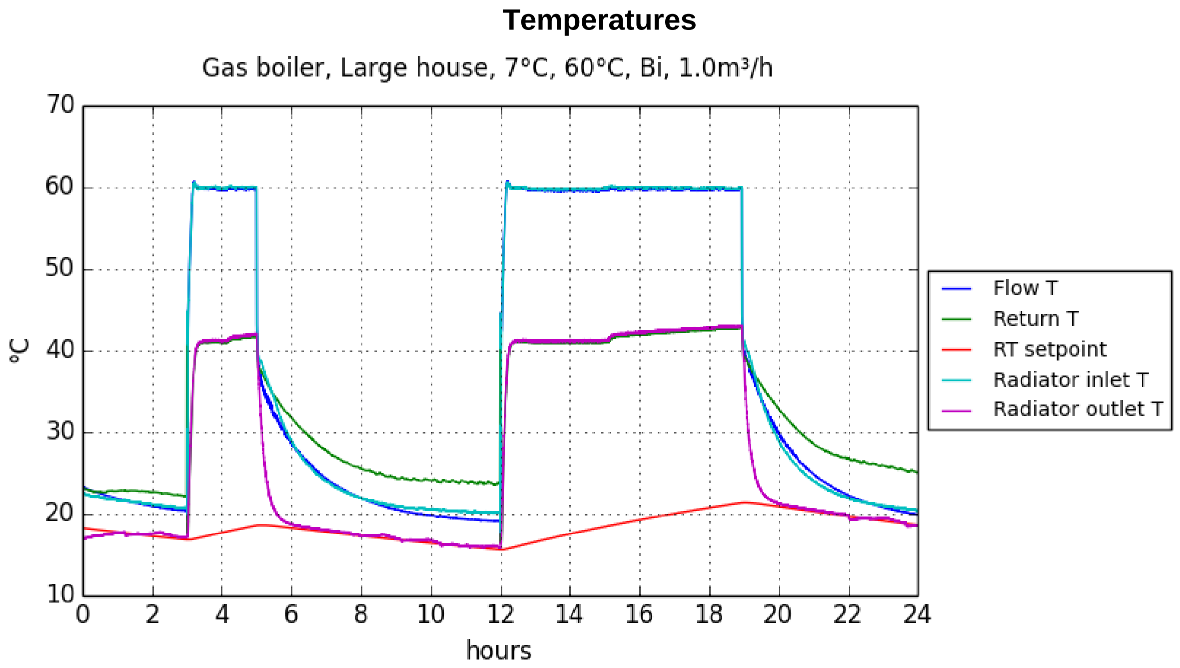
Test number	Outside T (°C)	Regime	Flow (m^3/h)	Flow T (°C)	Gas in (kWh)	Electric in (kWh)	Heat out from app (kWh)	Efficiency of appliance *[1]	Heat out from rads (kWh)	Efficiency of system *[2]	Mean Int T (°C)
080	7	Bi	1.0	60	196	3	196	99%	195	98%	18.2
083	0	Uni	1.0	60	325	4	317	97%	316	96%	18.5
092 *[3]	7	Uni	1.0	45	221	3	222	99%	221	99%	19.8
090 *[3]	0	Cont	1.0	45	342	4	342	99%	341	99%	20.9

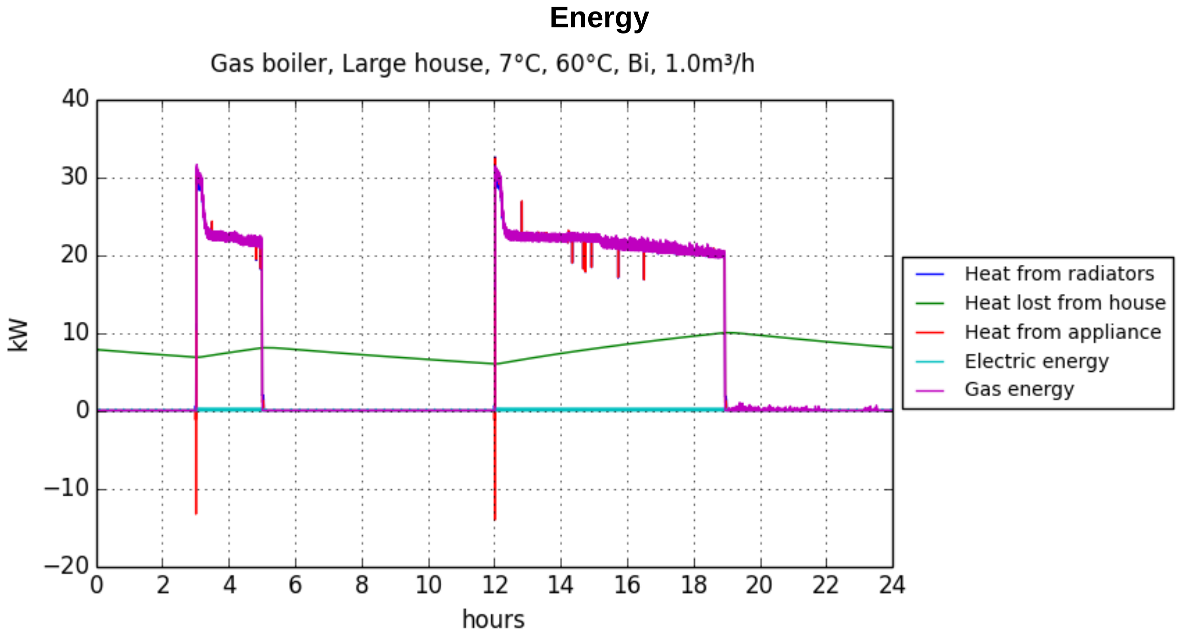
*[1] Equivalent to the instantaneous efficiency averaged over 24 hours.

*[2] Assuming no domestic hot water (DHW) use.

*[3] These tests have been corrected to allow for very high humidity and temperatures at the air inlet to the boiler, using the methods described in the Good Laboratory Practice for full and part load efficiency measurement for boilers (Revision of the document 1998-2000, Version 08, www.dgc.dk/labnet)

Test number 080





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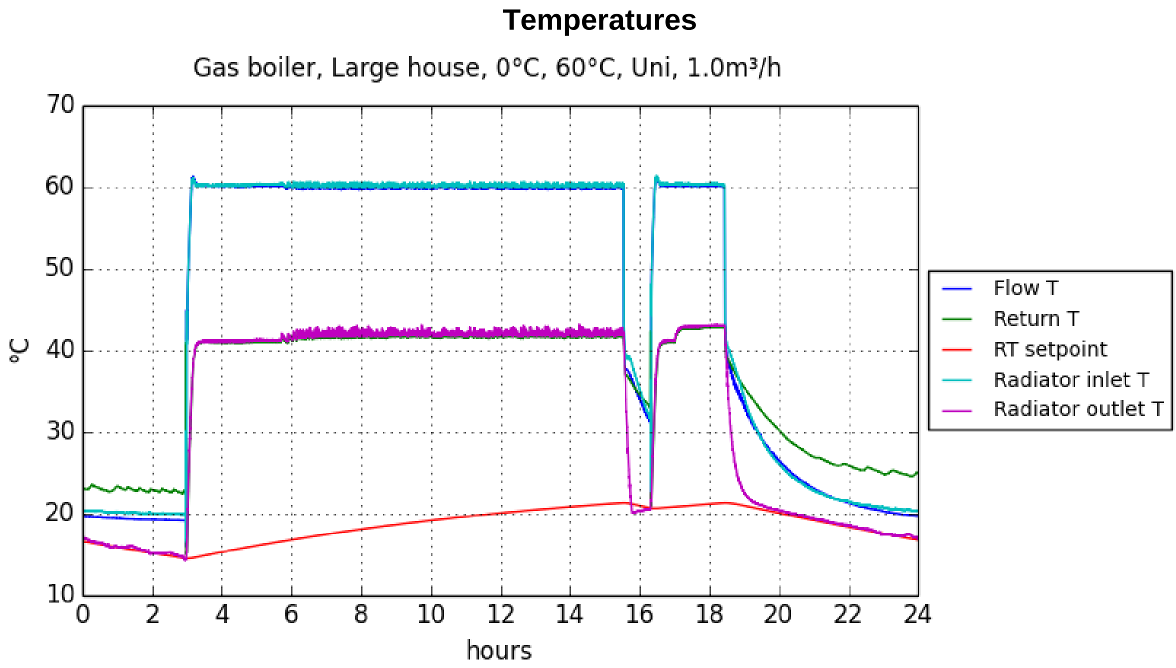
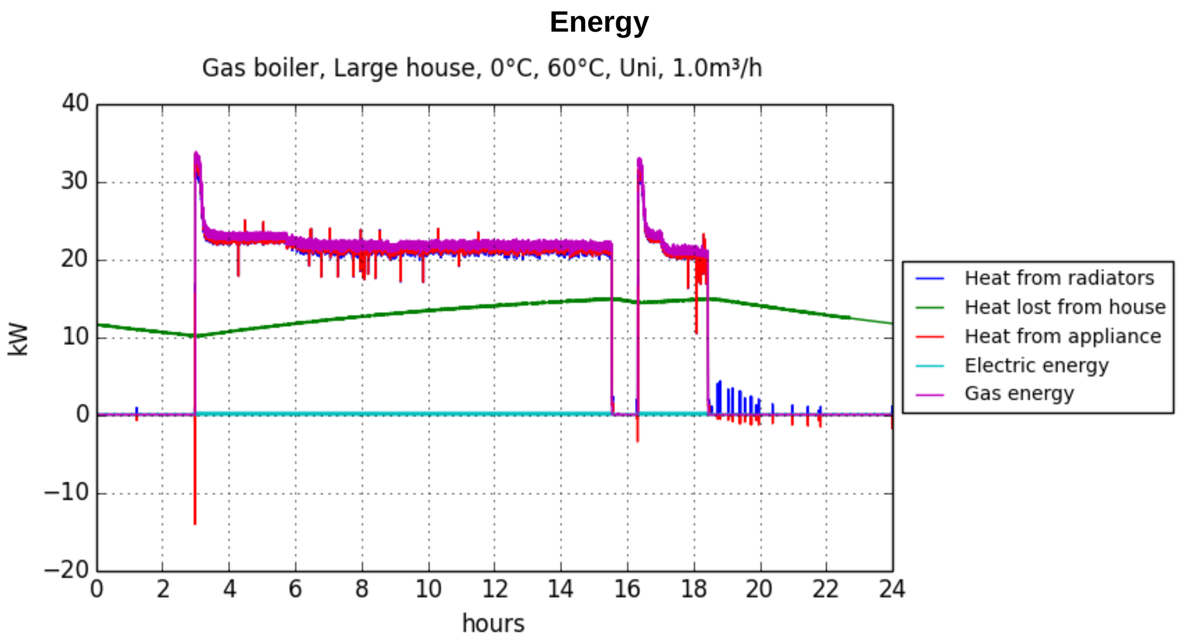
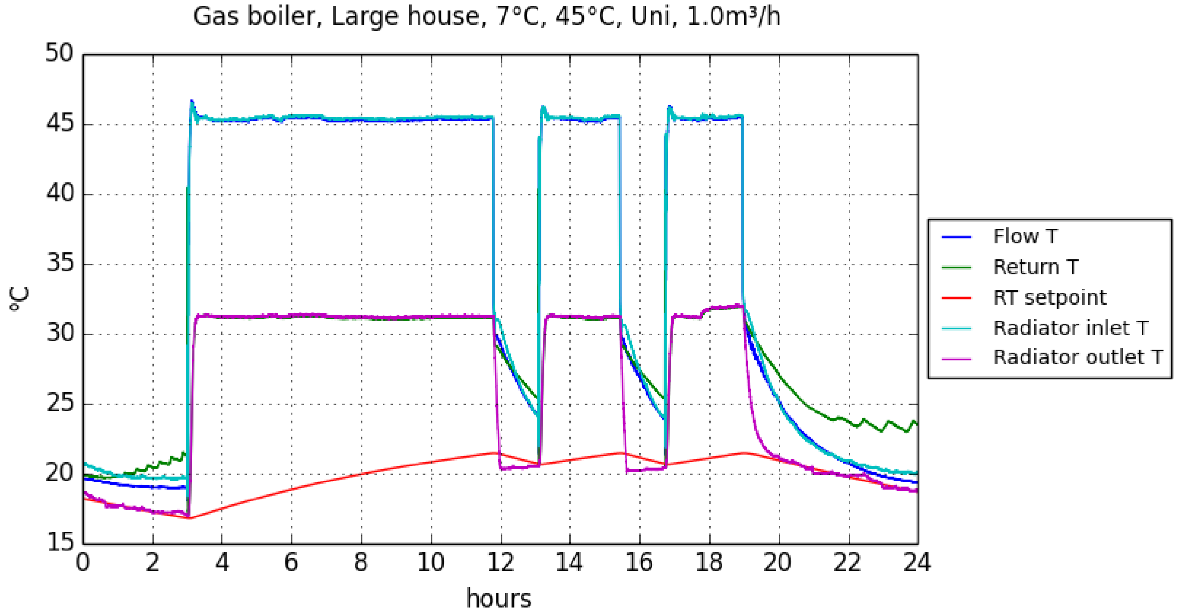


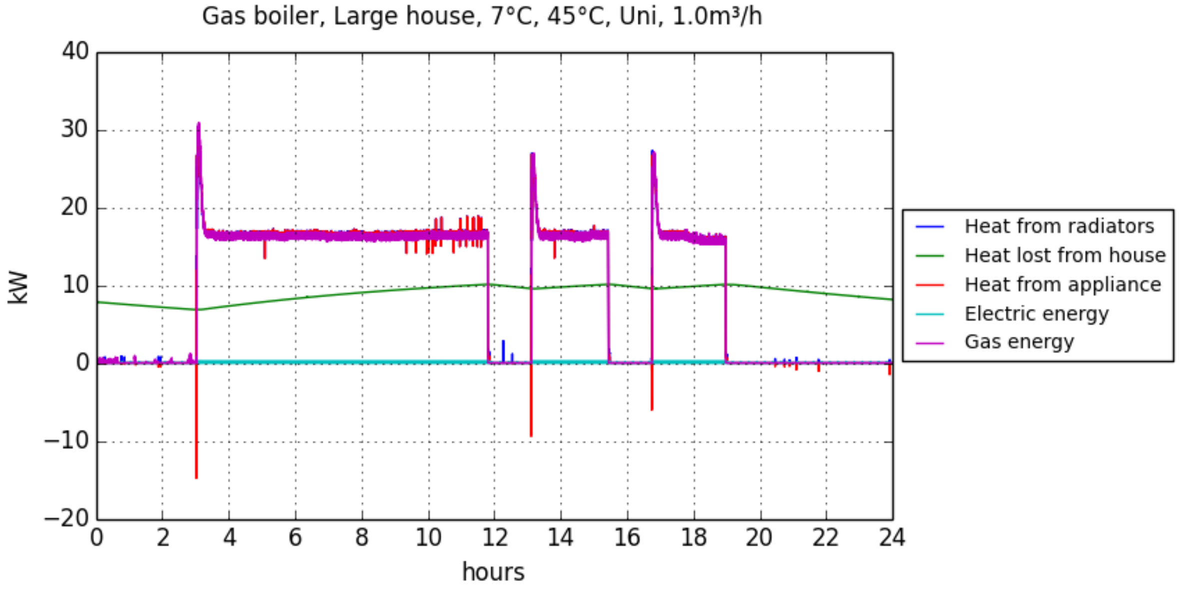


Test number 092

Temperatures



Energy



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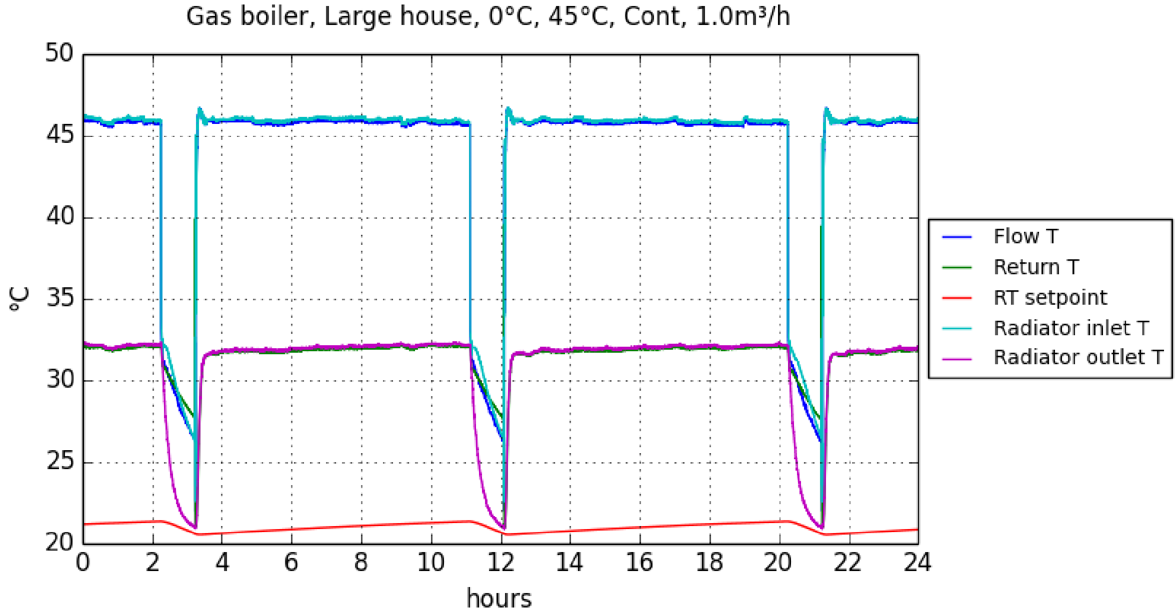

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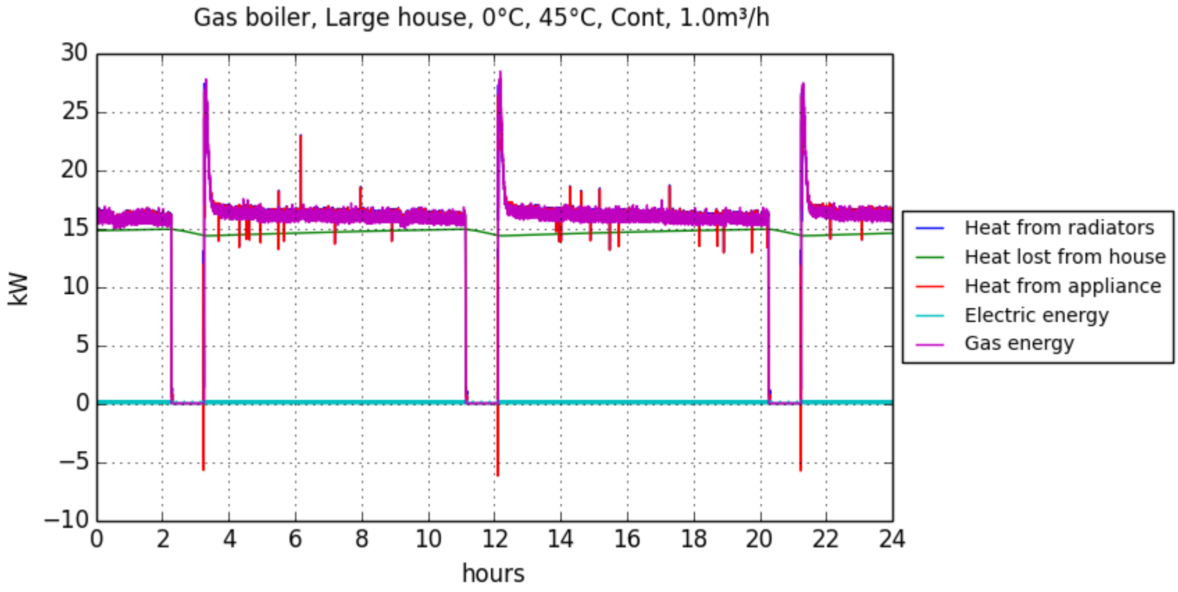


Most of the time the boiler can be seen to operate between 17-23kW; the system switches on/off based on the room thermostat and there is no cycling of the gas boiler on water flow temperatures.

The efficiency of a modern condensing gas boiler is dominated by water return temperature. The following table shows the average flow and return temperatures when the boiler was in operation.

Test number	**Flow T (°C)**	**Return T (°C)**	**Delta T (°C)**	**Efficiency of appliance** (based on gas and electricity)	**Efficiency of appliance** (based on gas only)
080	59	41	18	99%	99%
083	60	41	19	97%	98%
092	45	31	14	99%	99%
090	46	32	14	99%	99%

The typical lab efficiencies (on a gas-only basis) for these units at 30°C return and 37°C flow temperature (30% gas input) are 97-98%[10]. The measured efficiencies of 98-99% may be slightly higher than expected, but this is likely due the limits of uncertainty of the instrumentation.

The gas boiler tests showed that the radiator sizes were the limiting factor; although the gas boiler never operated at its full output (28kW), it operated around 22kW with an outside temperature of 0°C (flow temperature 60°C) reducing to 17kW with an outside temperature of 7°C (flow temperature 45°C). This reduced output in CH mode is in accord with control strategy adopted by many modern condensing boilers[11].

With an external temperature of 7°C and bimodal operation, the house did not reach the set point temperature in the morning, but this is frequently observed[12].

The first unimodal test was carried out with an external temperature of 0°C and required the gas boiler to operate almost continuously for the operational period, although under significant modulation. The second unimodal test with 45°C flow temperature gave an efficiency that was 4% higher than the 60°C flow test. At 7°C external temperature the system used 13% more gas in unimodal operation (with lower flow temperatures), than in bimodal operation. This can be attributed to the fact that the average house internal temperature was higher.

The continuous test was the only test to maintain internal temperatures of 21°C. At 0°C external temperature, running the system continuously used 5% more gas than in unimodal, because the average internal temperature was higher.

3.2 Gas boiler in Small House (300W/K)

Table 2: Results from gas boiler in the small house (300W/K)

Test number	Outside T (°C)	Regime	Flow (m^3/h)	Flow T (°C)	Gas in (kWh)	Electric in (kWh)	Heat out from app (kWh)	Efficiency of appliance *1	Heat out from rads (kWh)	Efficiency of system *2	Mean Int T (°C)
108	7	Bi	1.0	60	90	3	86	93%	86	93%	18.8
109 *3	7	Uni	1.0	60	101	3	97	93%	95	91%	20.3
106	0	Uni	1.0	60	141	3	133	93%	132	92%	19.0
099	7	Uni	1.0	45	97	3	96	96%	96	96%	20.0
103	0	Uni	1.0	45	137	3	136	97%	136	97%	18.9
188	0	Cont	1.0	45	148	6	148	96%	144	93%	20.9

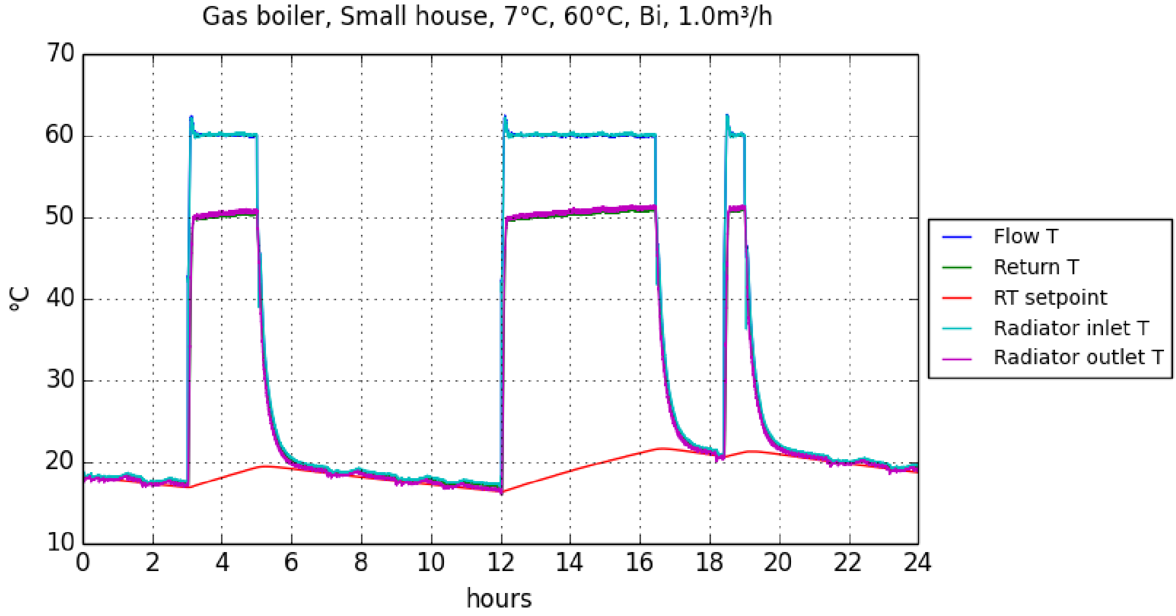
*1 Equivalent to the instantaneous efficiency averaged over 24 hours.

*2 Assuming no domestic hot water (DHW) use.

*3 In addition to the original test regime, an extra test was undertaken at 7°C, under unimodal conditions.

Test number 108

Temperatures



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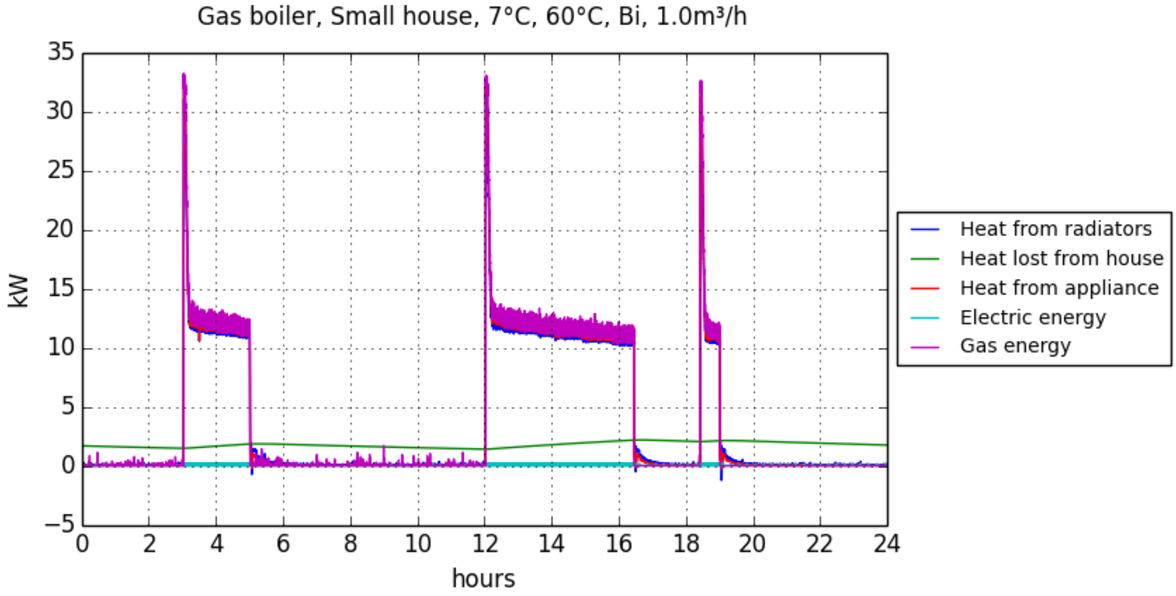

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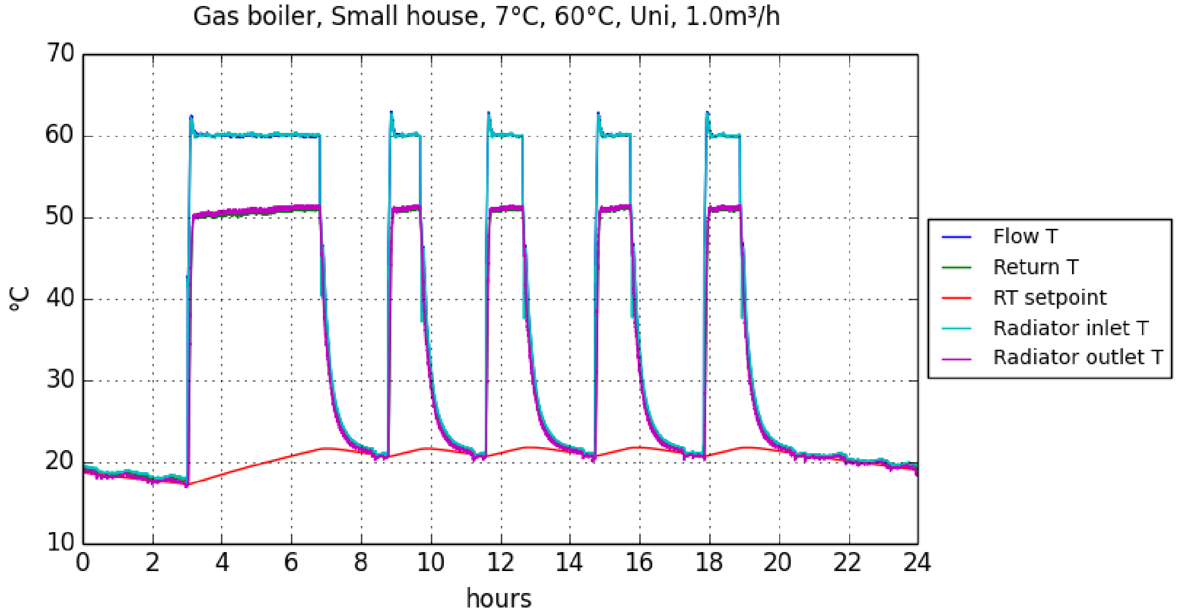

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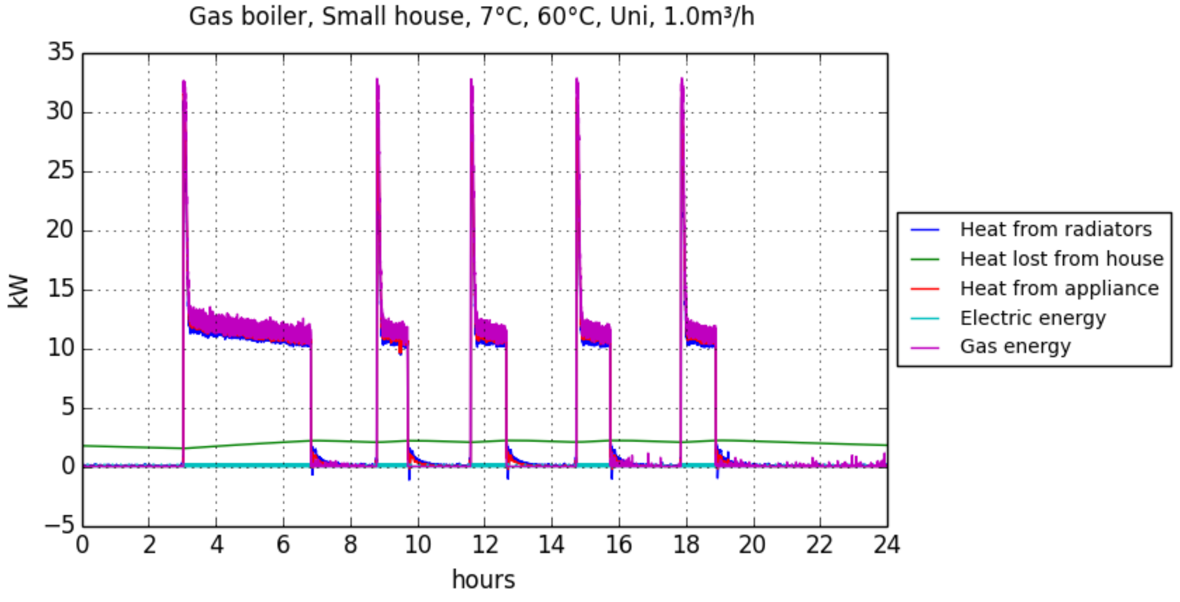

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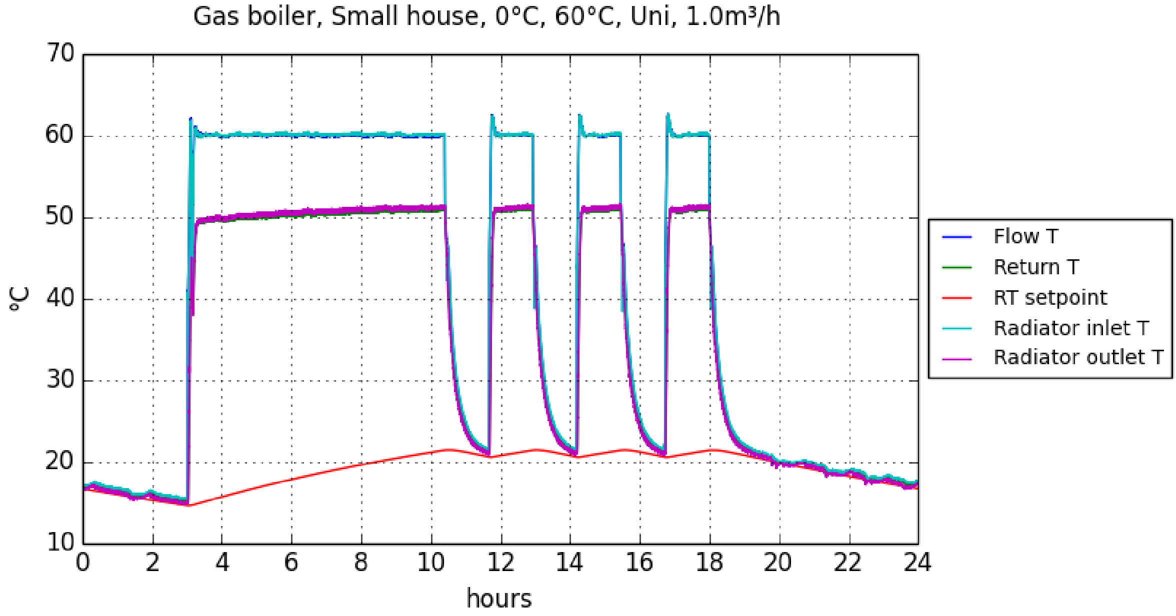
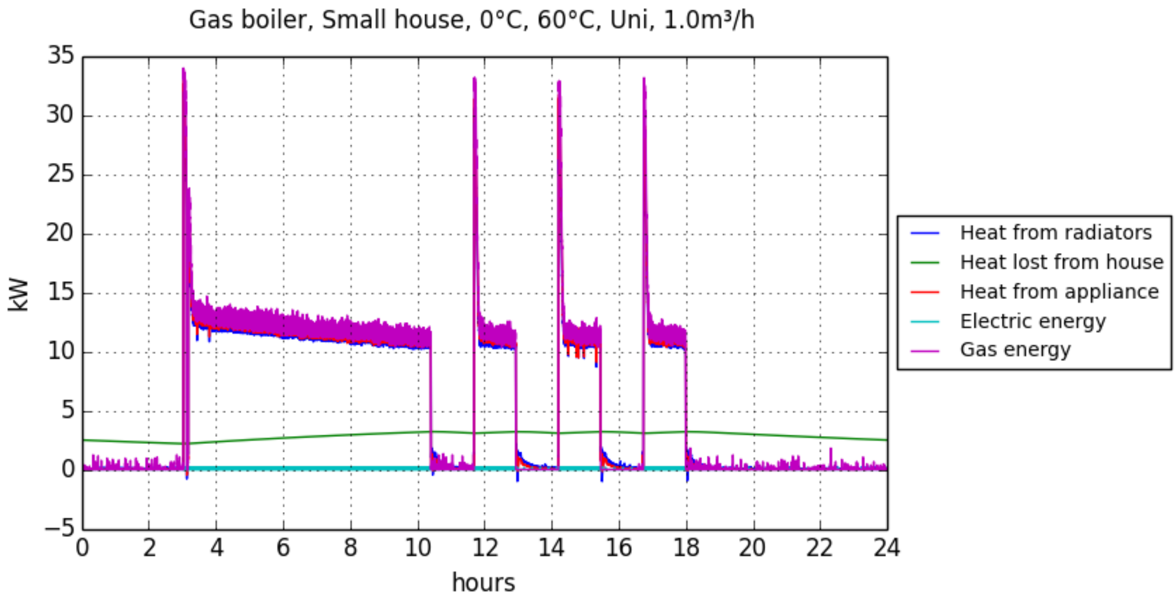
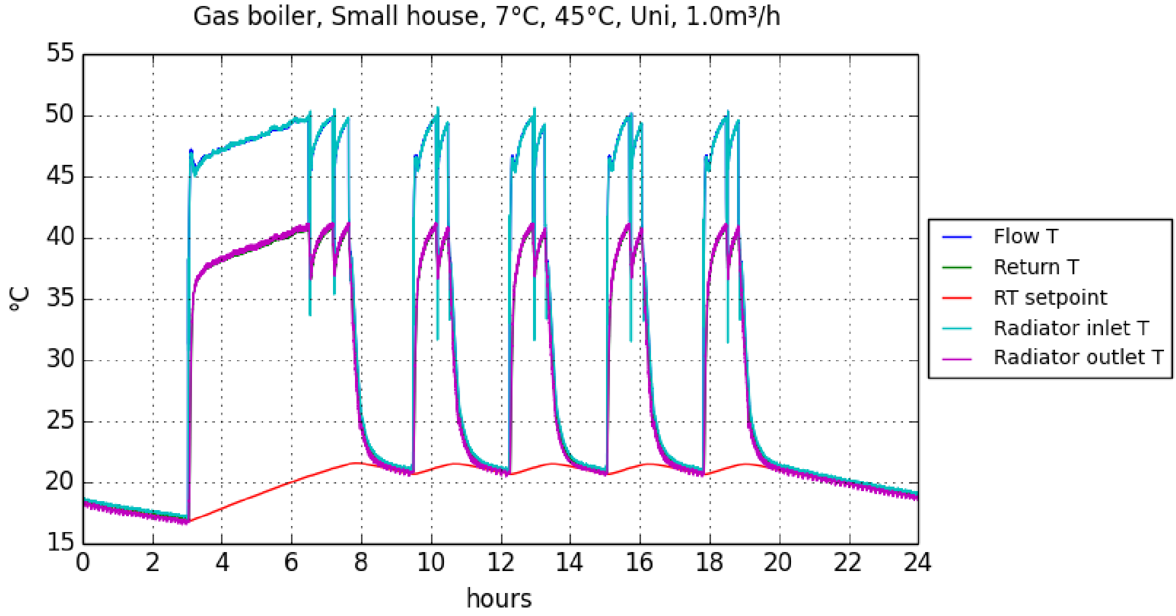


Energy



Test number 099

Temperatures



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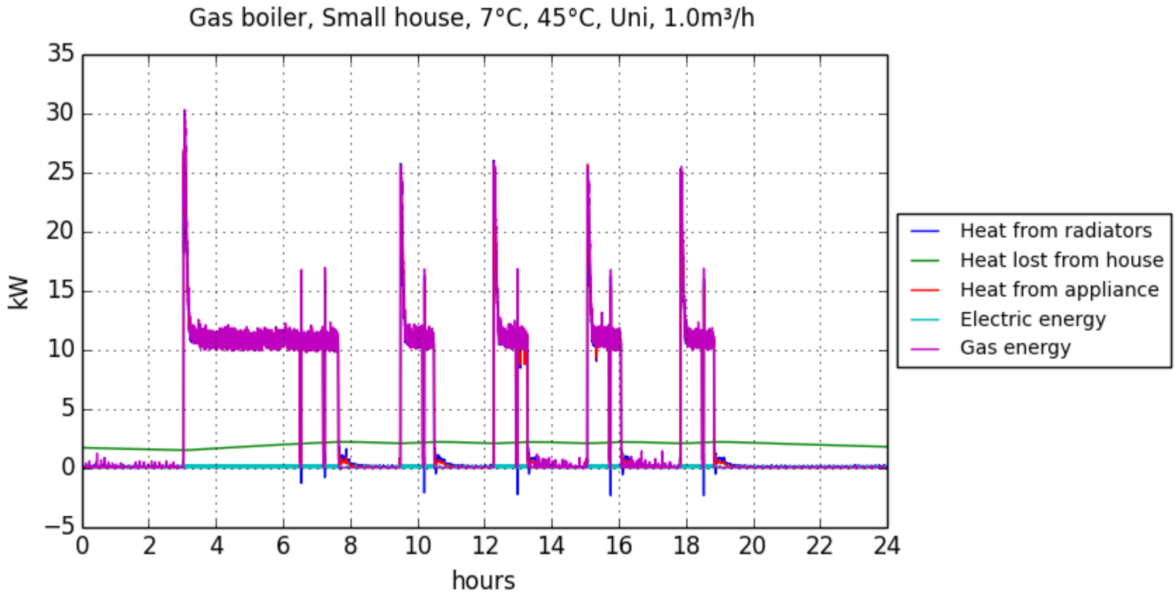
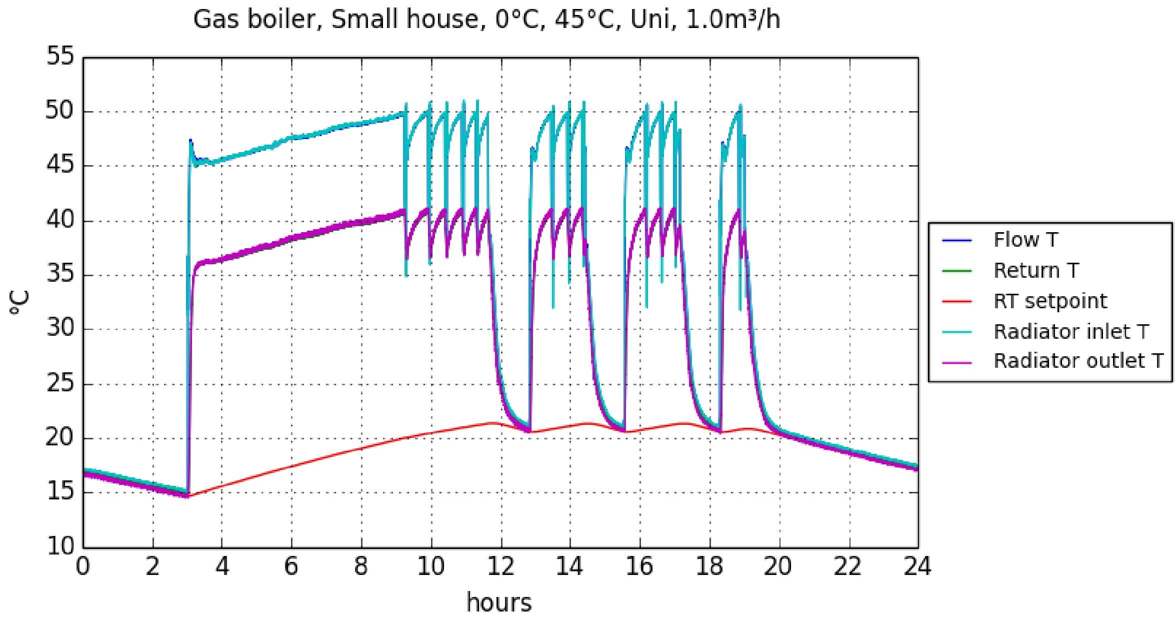


Test number 103

Temperatures



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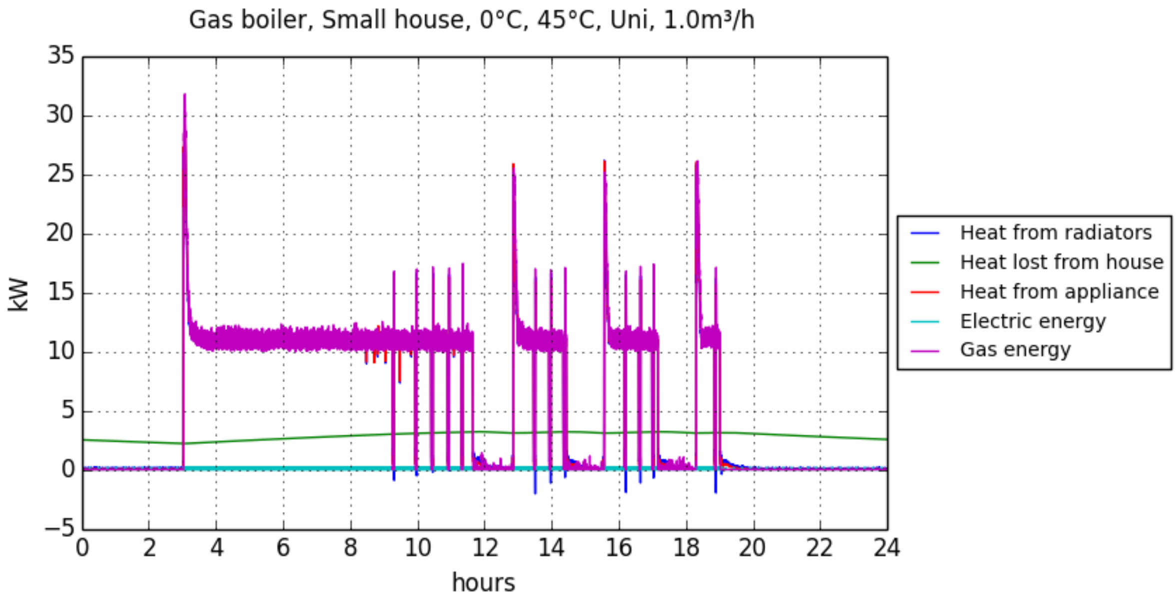

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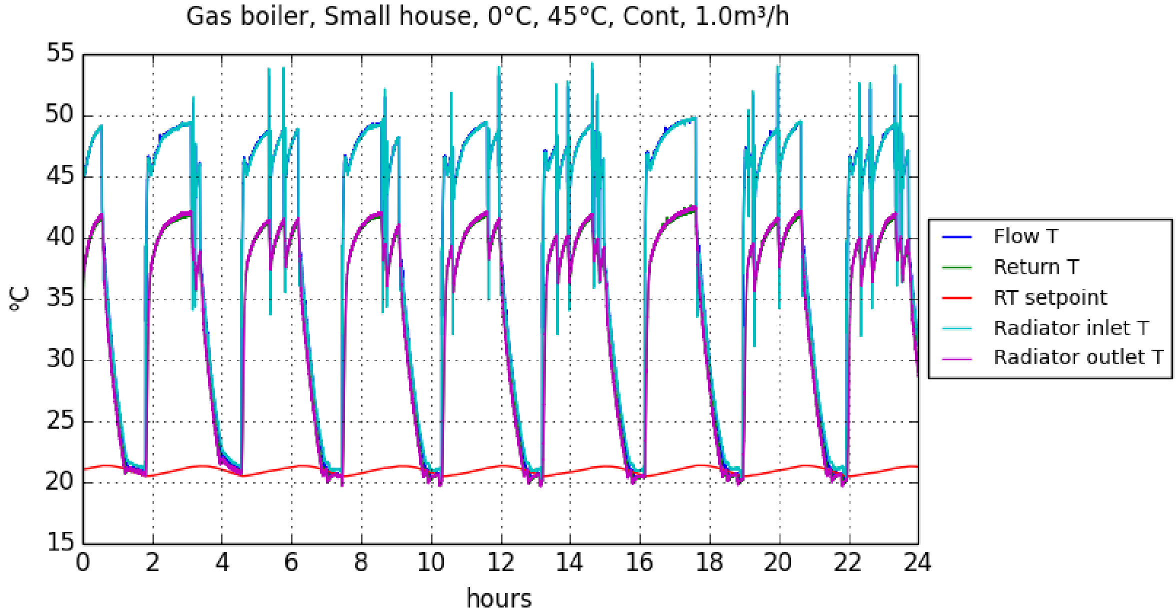
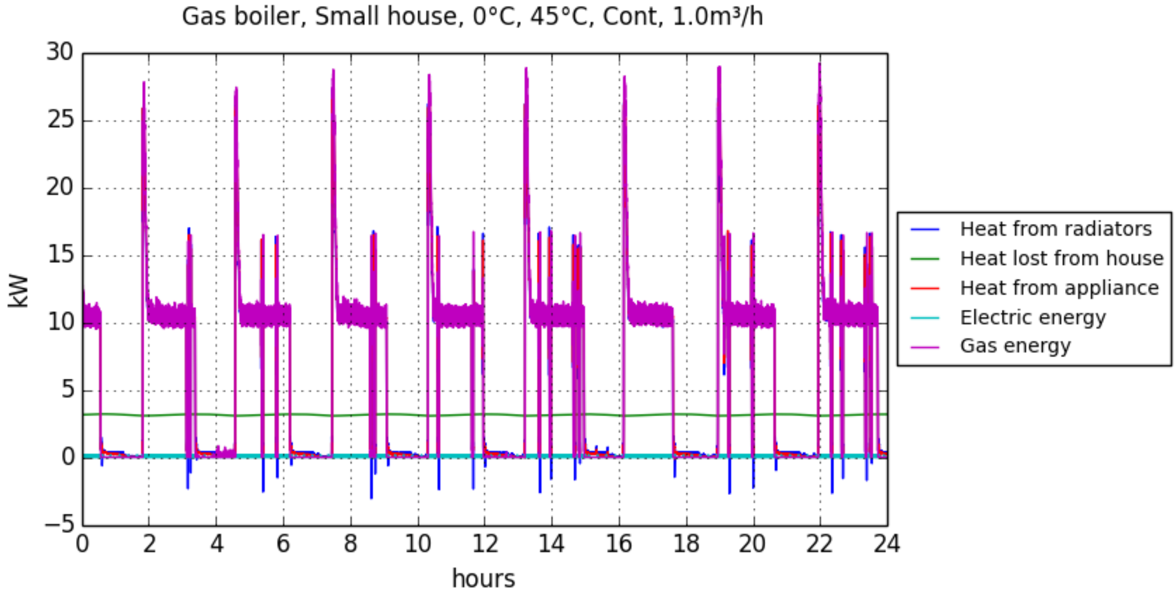
Temperatures



Energy



Most of the time of boiler can be seen to operate between 10-14kW. In contrast with the large house, when operated at a 45°C flow temperature, the boiler begins to cycle on water flow temperature at a rate of 3 cycles/hour. The system also turned on/off more frequently than in the large house. Both of these effects are expected, as in the smaller house there will be a less water in the heating system, which will heat up more quickly; as the house has a lower heat loss coefficient, it will also heat up more quickly.

The efficiencies were lower in these tests which may be as a result of the increased cycling. Increased cycling leads to increased losses due to purging prior to ignition and loss of unburnt gas during ignition. The radiator temperature for the 45°C tests can be seen to rise to 50°C throughout each cycle before the gas boiler turned off and started back up again. During start up the system efficiency was decreased as can be seen on the energy graph, the gas boiler (pink, bottom graphs) ignites at ~28kW, and quickly falls to the limitation of the radiator output (about 12kW).

This is the effect of cycling which decreases the efficiency and is more prevalent on warmer days in spring and summer when the load is very light. As indicated above, the 28kW gas boiler is designed to supply a shower and is not sized on central heating demand; it is designed to modulate under normal CH use.

The radiator heat output was the limiting factor on this series of tests, with heat outputs decreased to 15kW at 60°C and 12kW at 45°C.

House temperatures were limited both by radiator area and gas boiler output. Again with an external temperature of 7°C, the house did not reach the set point temperature in the morning.

Tests were carried out with outside air temperatures of 0 and 7°C and water temperatures of 45 and 60°C. The efficiency was 4% lower when using flow temperatures of 60°C. As expected the warmer day yielded higher average internal temperatures.

Continuous operation used 8% more gas than unimodal at 45°C and 5% more gas than unimodal at 60°C. This is in good agreement with previous modelling of continuous and unimodal operation, which suggested on average a 7-8% increase in gas use when moving from unimodal to continuous heating[13].

3.3 ASHP in Small House (300W/K)

Table 3: Test results for ASHP in small house (300W/K)

Test number	Outside T (°C)	Humidity (%)	Regime	Flow (m^3/h)	Flow T (°C)	Electric in (kWh)	Heat out from app (kWh)	24 h Efficiency of appliance *[1]	Heat from rads (kWh)	24 h Efficiency of system *[2]	Mean Int T (°C)
115	7	— *[4]	Uni	1.0	60	34	97	289%	89	265%	19.5
124	0	60	Uni	1.0	60	56	140	251%	130	232%	17.7
120	7	— *[4]	Cont	1.0	60	37	110	295%	101	270%	20.9
122	0	59	Cont	1.0	60	66	162	245%	148	224%	20.8
132	7	58	Cont	1.0	45	32	105	330%	98	309%	20.9
129 *[3]	7	75	Cont	1.15	45	33	101	308%	96	293%	20.9
126	0	45	Cont	1.0	45	59	160	271%	150	254%	20.8
127 *[3]	0	47	Cont	1.15	45	57	152	266%	141	248%	20.7

*[1] Equivalent to the instantaneous coefficient of the performance (COP) averaged over 24 hours.

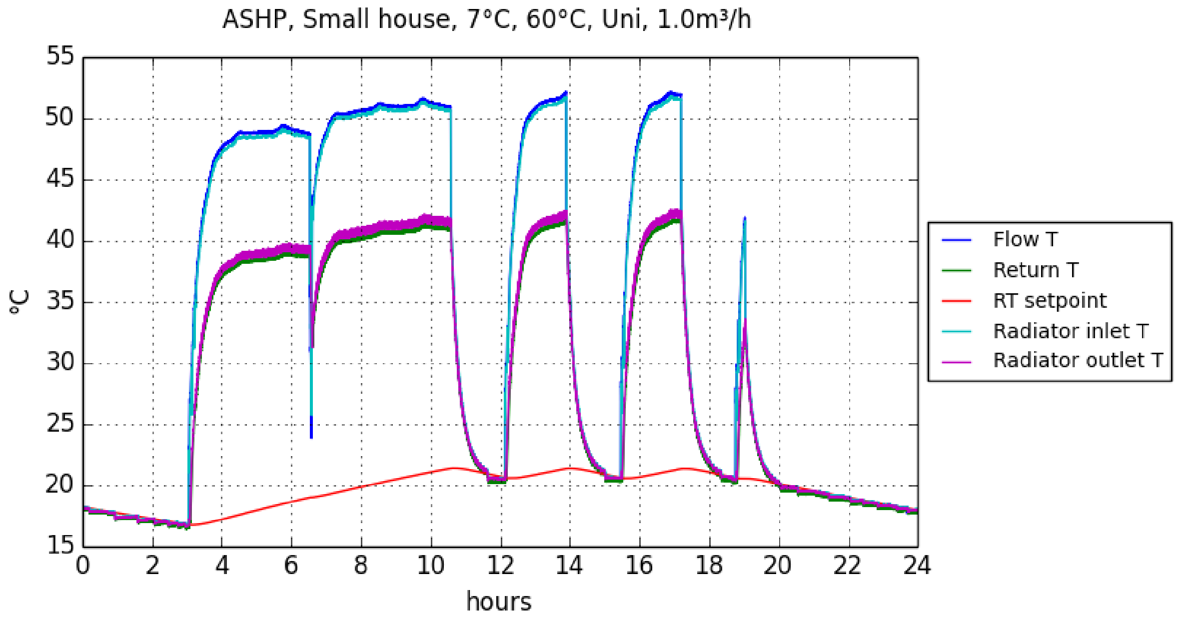
*[2] Equivalent to SPFH4, assuming there are no buffer tanks or domestic hot water (DHW) use.

*[3] In addition to the original test regime, extra tests were undertaken with different flow rates.

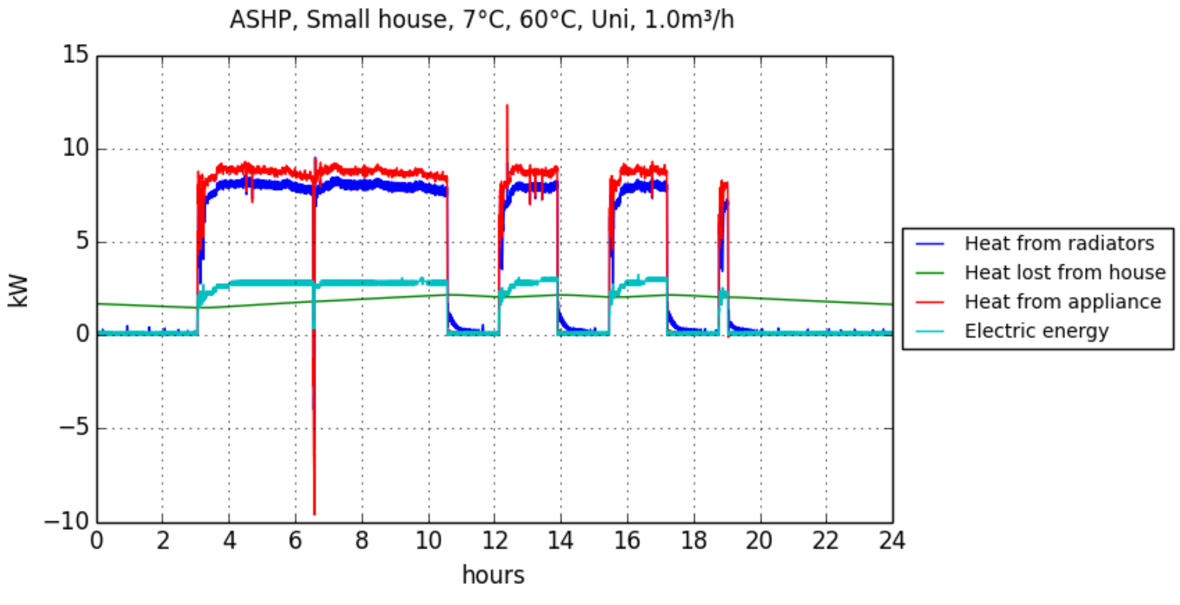
*[4] Measurement instrumentation issues, set point was 60%.

Test number 115

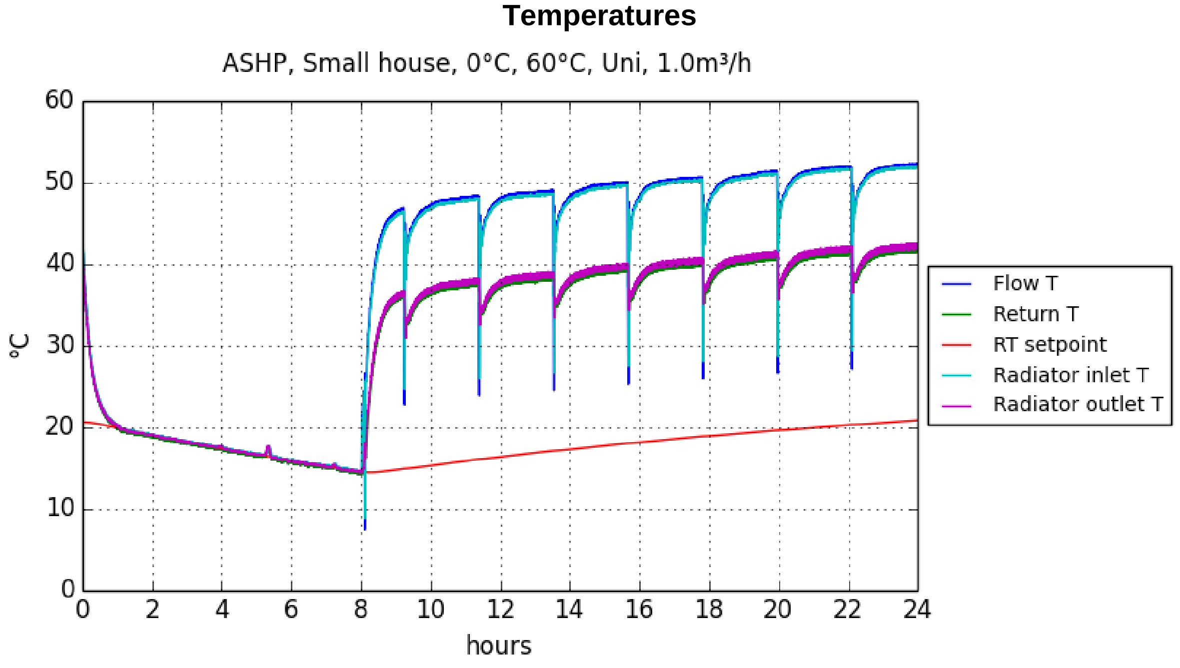
Temperatures

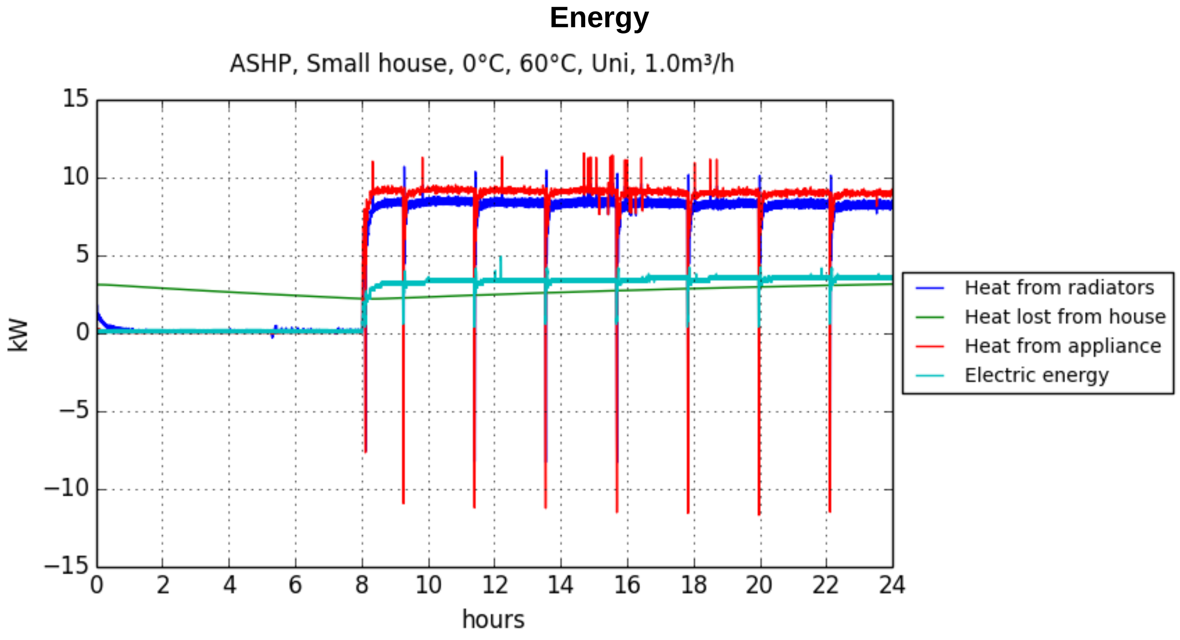


Energy

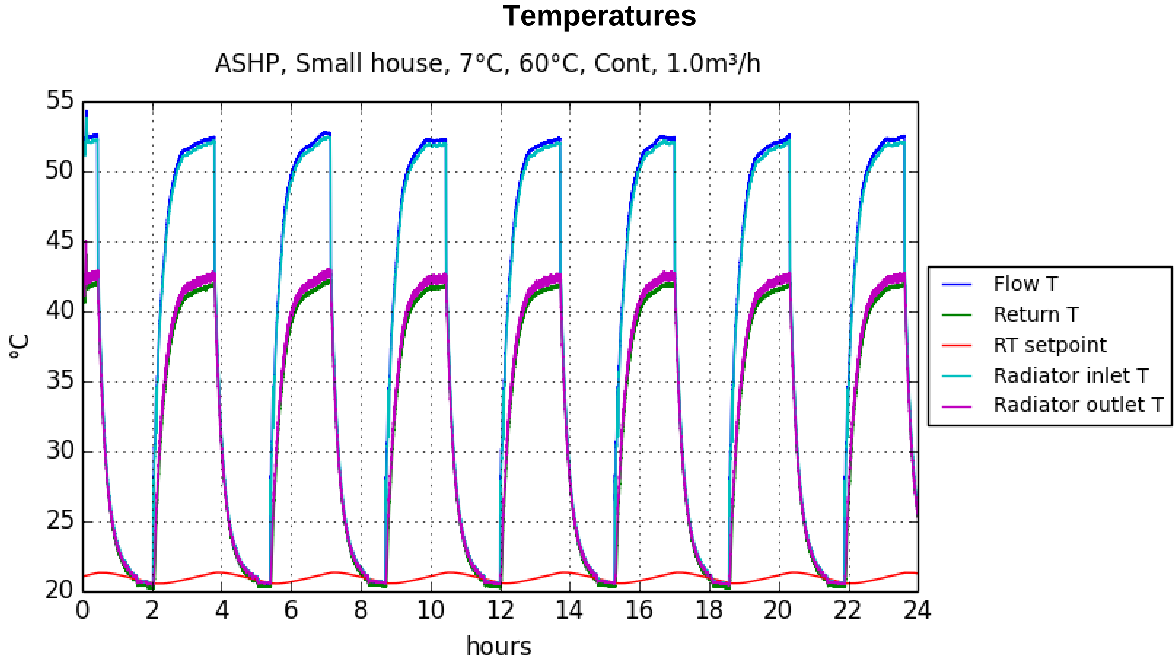


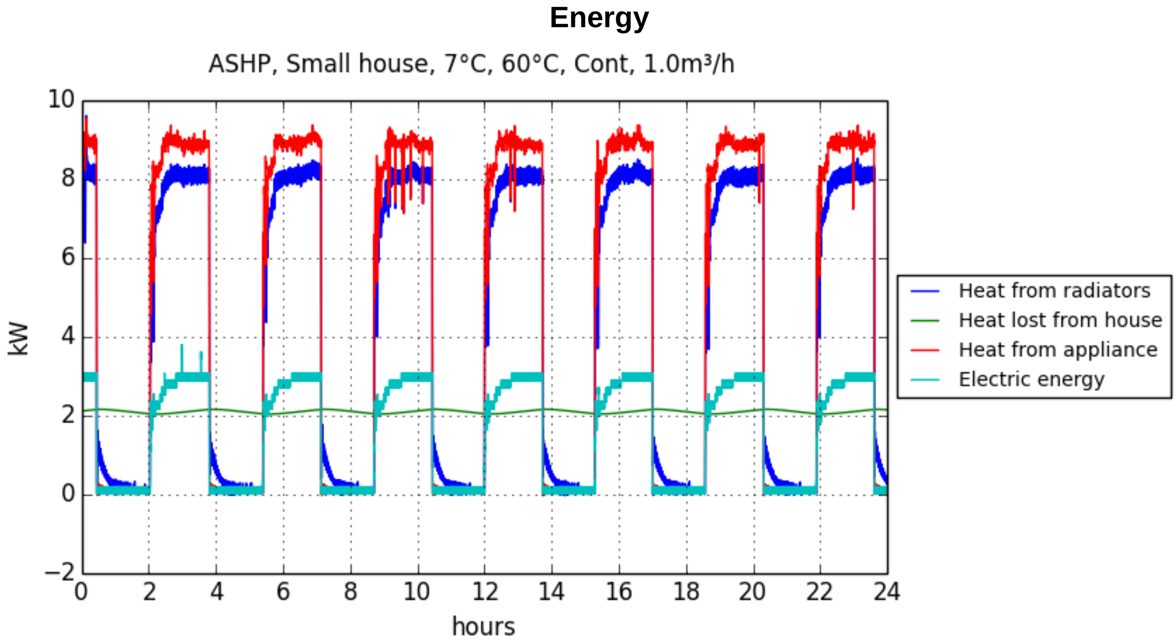
Test number 124



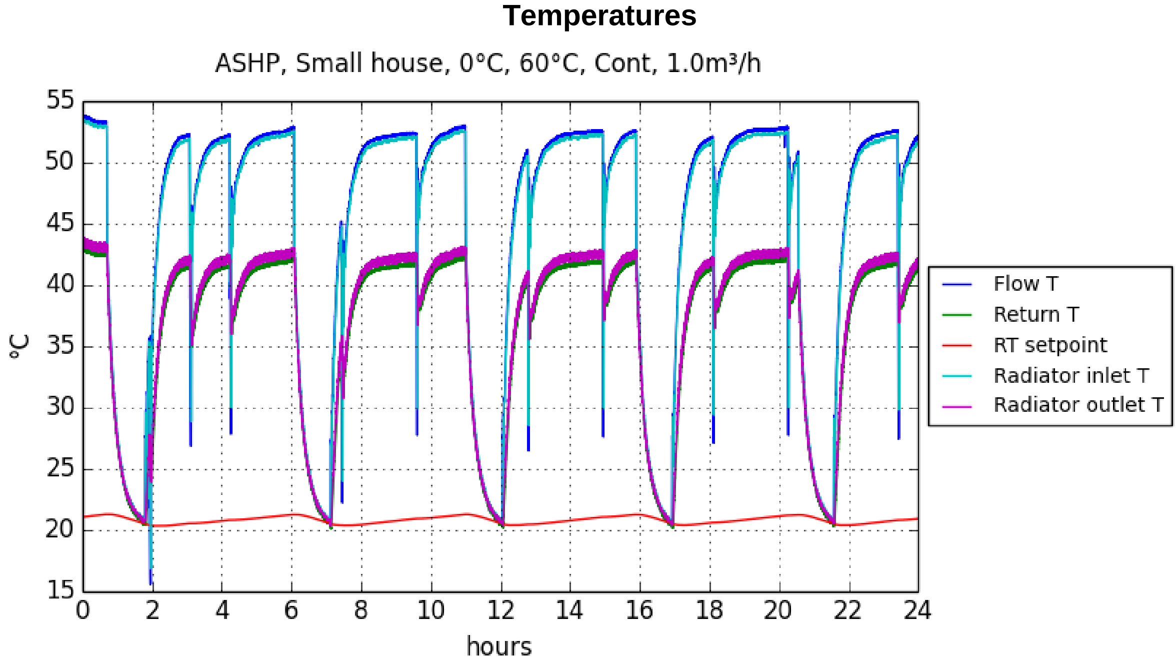


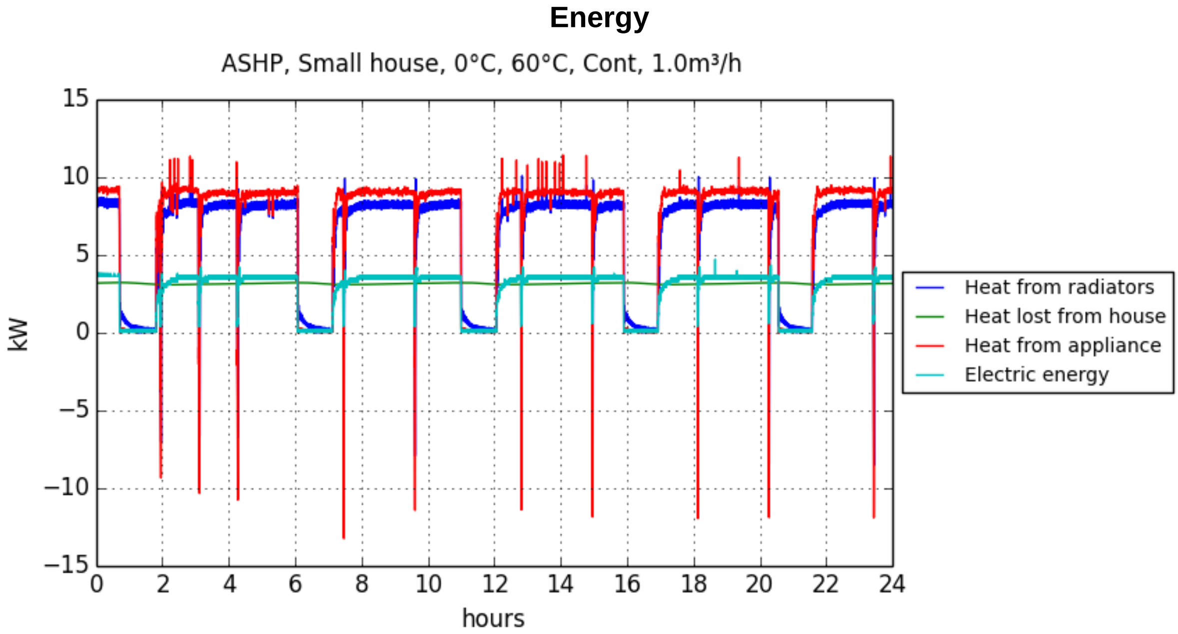
Test number 120





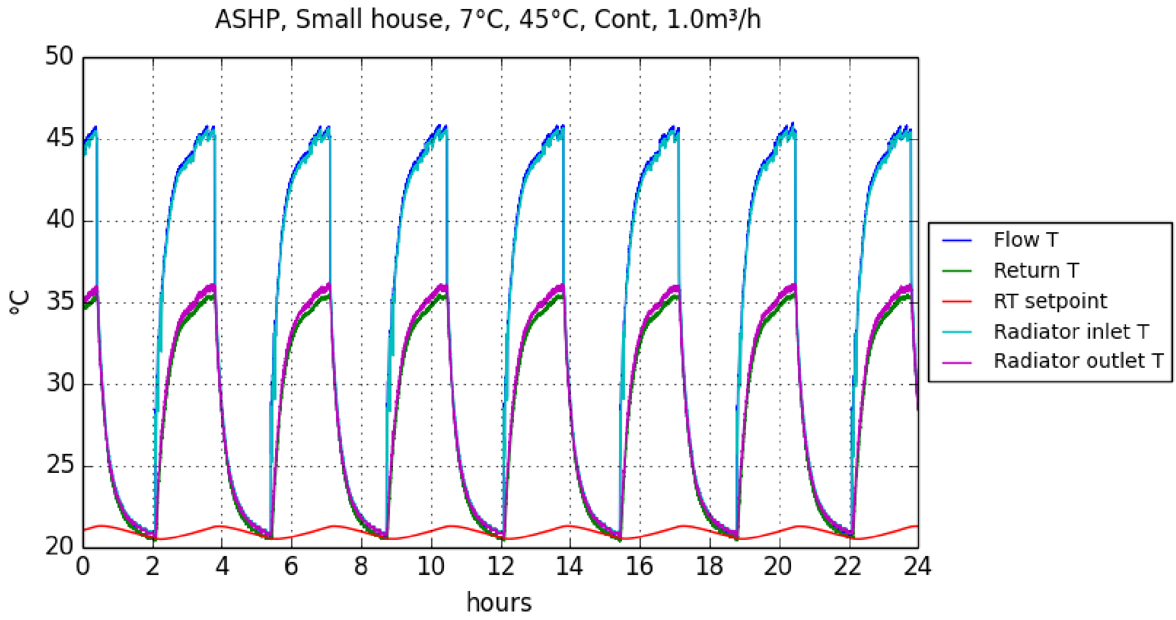
Test number 122



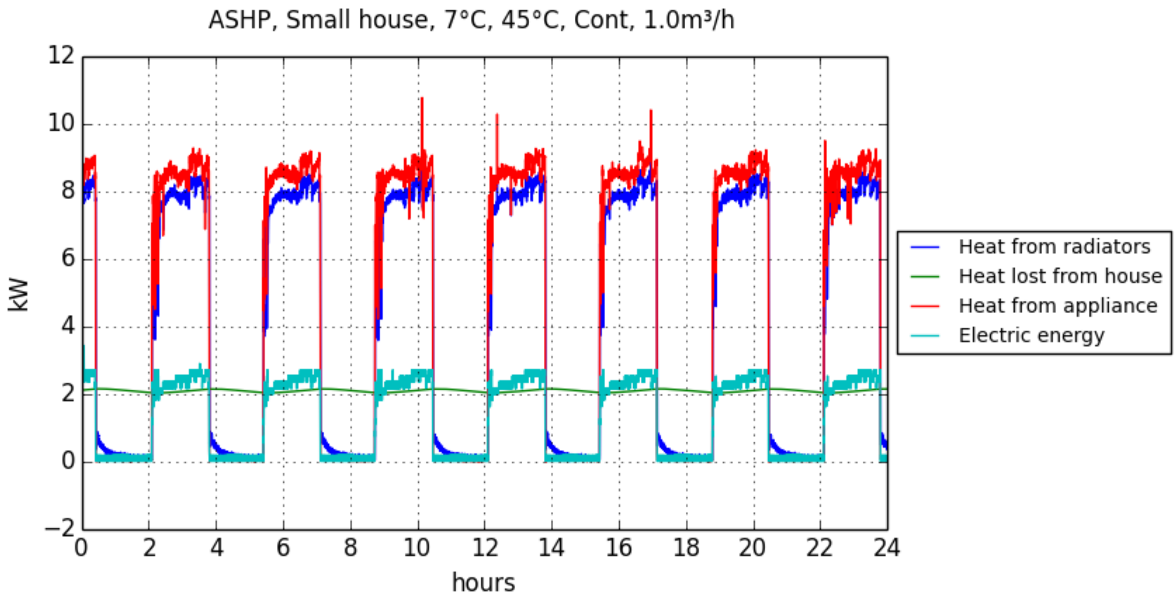


Test number 132

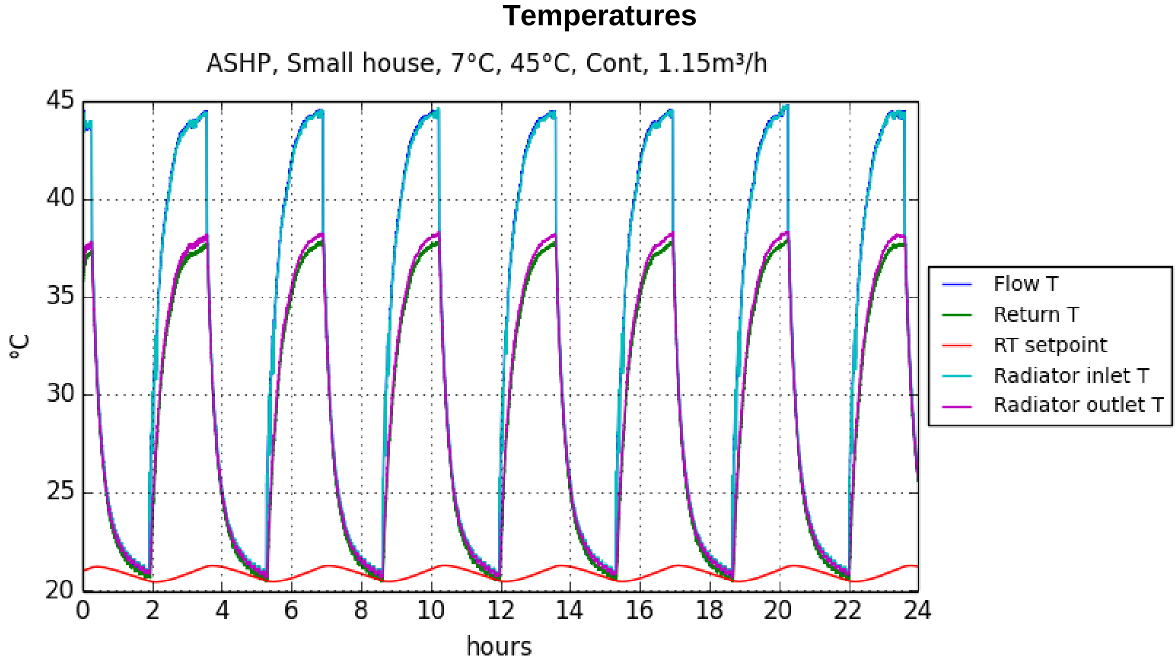
Temperatures

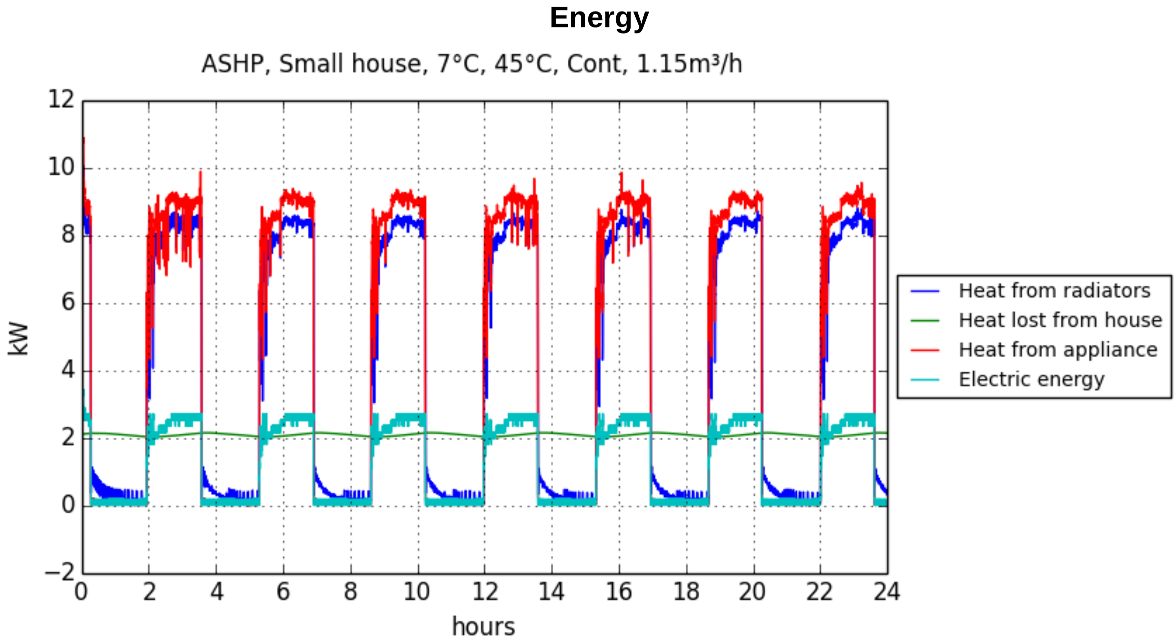


Energy

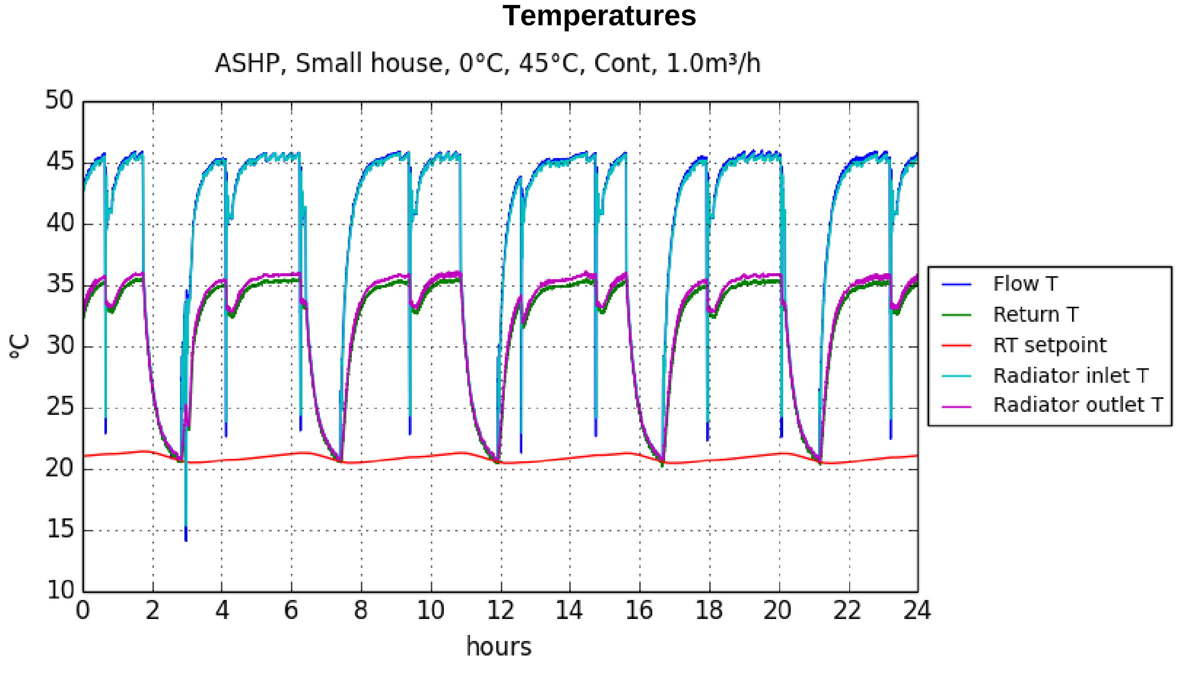


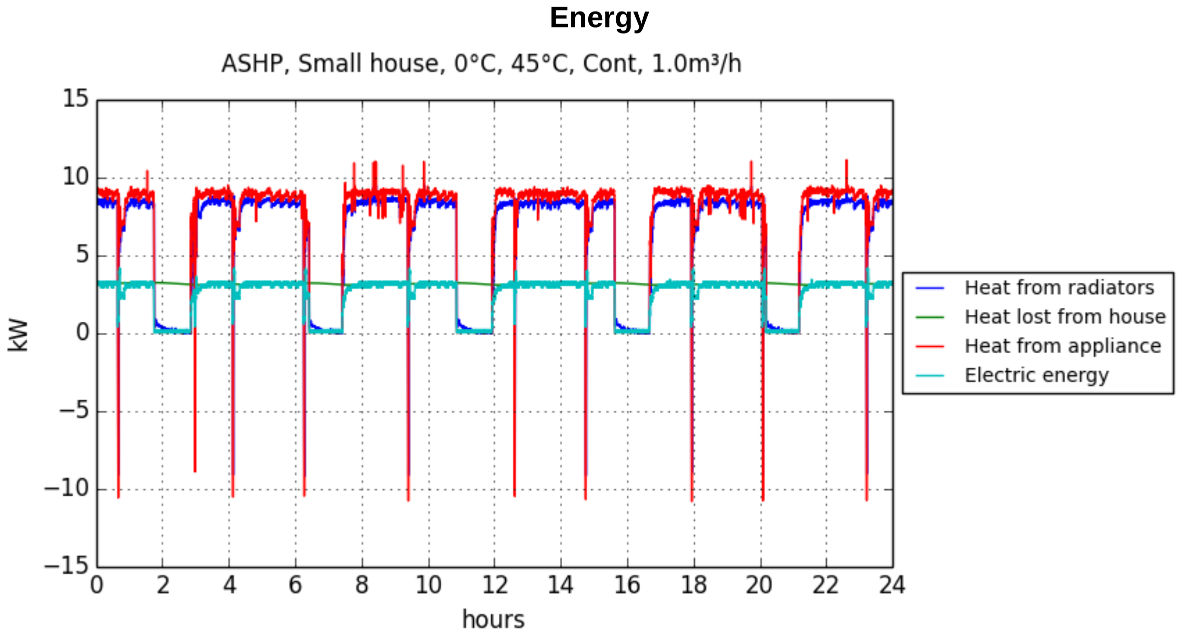
Test number 129



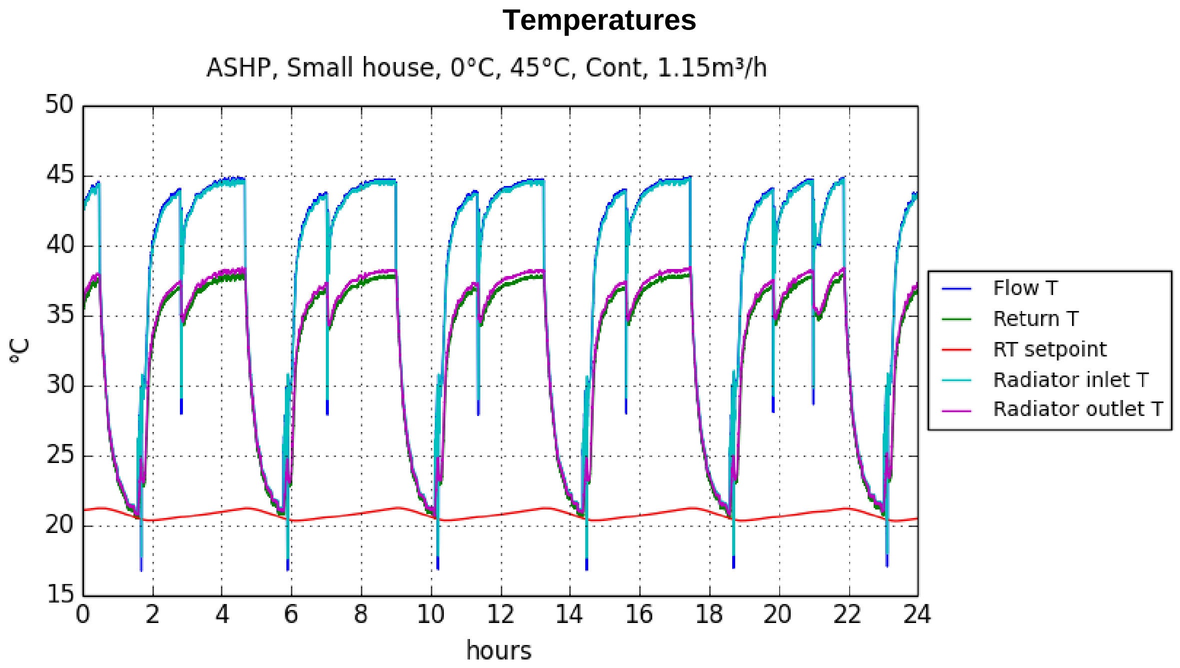


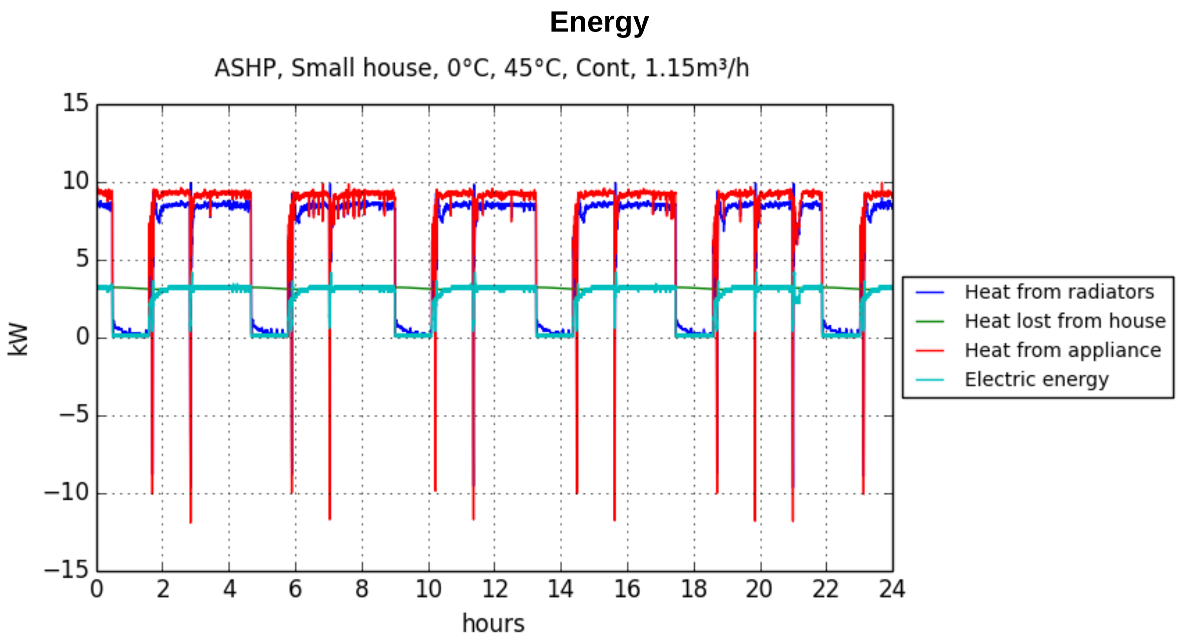
Test number 126





Test number 127





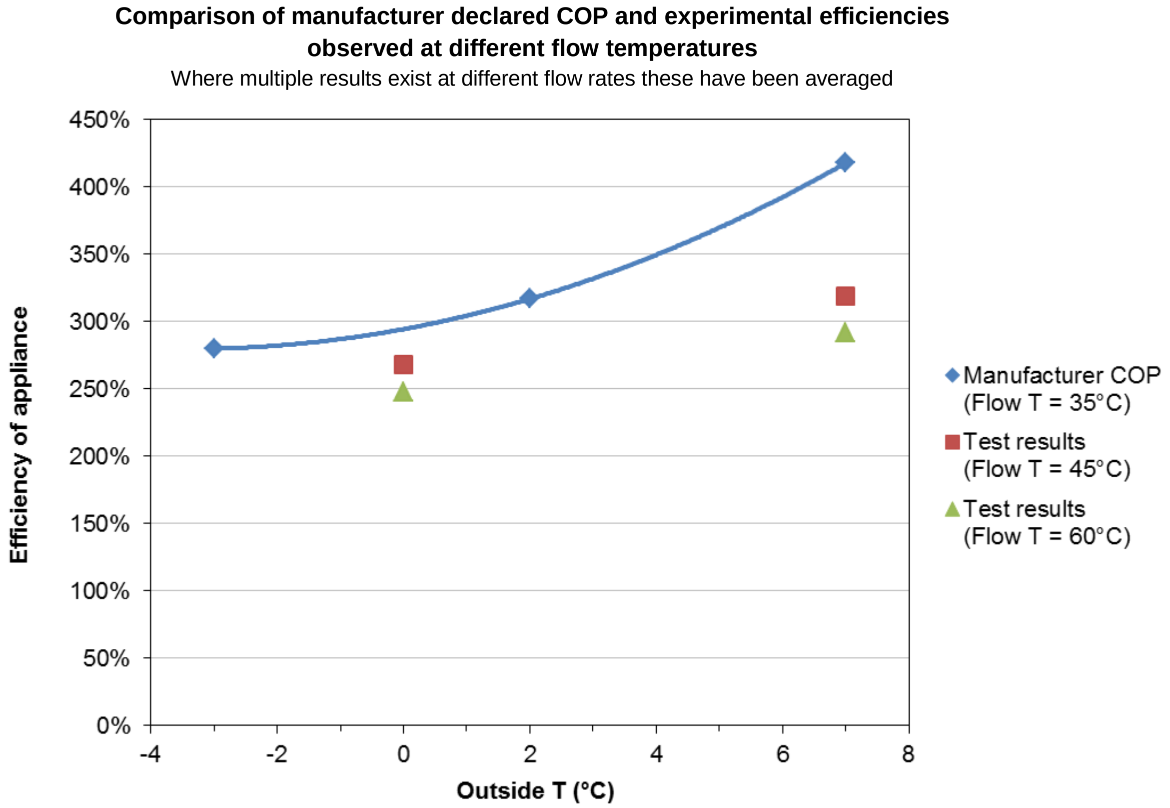
The ASHP operated relatively continuously with heat output of 8-9kW, with little evidence of cycling on water flow temperature. If the room temperature set point was reached then the system switched on/off with a period of around 4-5 hours.

Defrost cycles are clearly visible as the electrical demand falls close to zero and the appliance absorbs heat from the system (i.e. has a negative energy flow.) This defrosting is very infrequent with an external temperature of +7ºC, but is very evident at 0ºC (for example in test runs 124 and 127.)

The flow temperatures of 60°C required by a conventional radiator system were not achieved with this ASHP (as anticipated). The highest temperature reached in the 60°C (notional) tests was 54.3°C, with the mean flow temperature when the ASHP was running (at 60°C notional) averaging between 48 and 49.8°C. This is because ASHPs do not provide energy efficiently at high temperatures, to achieve high flow temperatures supplementary/booster heaters would be required.

During the 45°C tests, it was found that the maximum temperature seen was 45.9°C while the average temperature during operation was 42°C. This was because the ASHP took a long time to get up to temperature. Attempting to reach these high water temperatures inevitably reduces instantaneous COP.

It is interesting to compare these values with the manufacturer's declared COP values; this is shown in the figure below. In view of the difference in operating temperatures the results are not unexpected. This does highlight that the effect of water flow temperature is substantive.



During the testwork, the ASHP was located in the temperature controlled environment ('blue box') and the dynamic rig located within the adjacent laboratory building. This means there was additional pipework, consisting of 2m in the blue box (at 0 or 7°C) +2.5m outside (at ambient temperature) + 2m inside (at laboratory temperature 20°C). This appears to equate to a difference in the delta T of 1°C, which is about 10kWh over the 24 hour test period. This means the heat delivered to the radiators can be 0.8kW lower than the heat supplied by the appliance. This is in many ways a reflection of reality in many ASHP installations.

Defrost cycles were generally only observed when the external temperature was at 0°C, however there was 1 defrost cycle on the unimodal 7°C cycle at flow temperature of approaching 60°C, during the prolonged on-period.

The radiator sizes were not the limiting factors in these tests because the output was generally approaching the ASHP manufacturer's stated output of 8.5kW, so the output of the ASHP was the limiting factor.

3.4 GAHP in Large House

Table 4: Test results for GAHP in large house (700W/K)

Test number	Outside T (°C)	Humidity (%)	Regime	Flow (m^3/h)	Flow T (°C)	Gas in (kWh)	Electric in (kWh)	Heat out from app (kWh)	24h Efficiency of appliance *[1]	Heat out from rads (kWh)	24h Efficiency of system *[2]	Mean Int T (°C)	
178	7	57	Bi	1.5	60	156	16	185	108%	185	108%	18.2	
134	0	64	Bi	1.15	60	185	17	214	106%	211	104%	14.9	*[4]
136	0	52	Uni	1.15	60	268	22	302	104%	296	102%	18.4	
184 *[3]	0	74	Uni	1.5	60	274	22	300	102%	300	102%	18.7	
170	7	55	Uni	1.5	45	165	19	214	116%	212	115%	19.7	
162	0	77	Cont	1.5	45	269	26	342	116%	338	114%	20.8	

*[1] Equivalent to the instantaneous coefficient of the performance (COP) averaged over 24 hours.

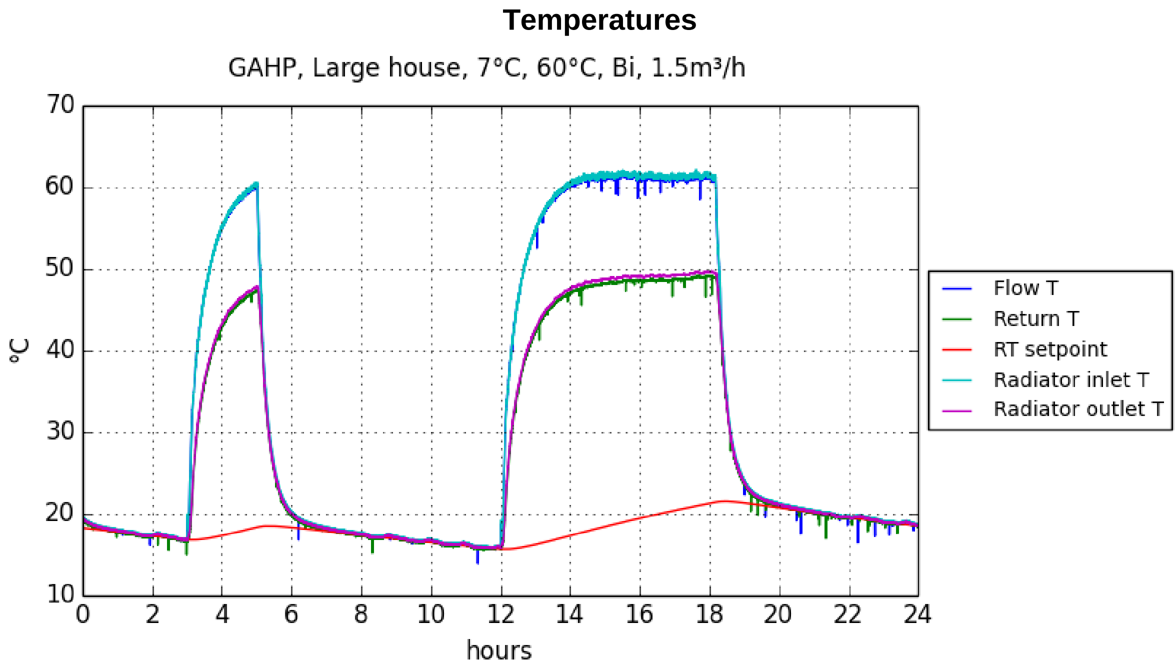
*[2] Equivalent to SPFH4, assuming there are no buffer tanks or domestic hot water (DHW) use.

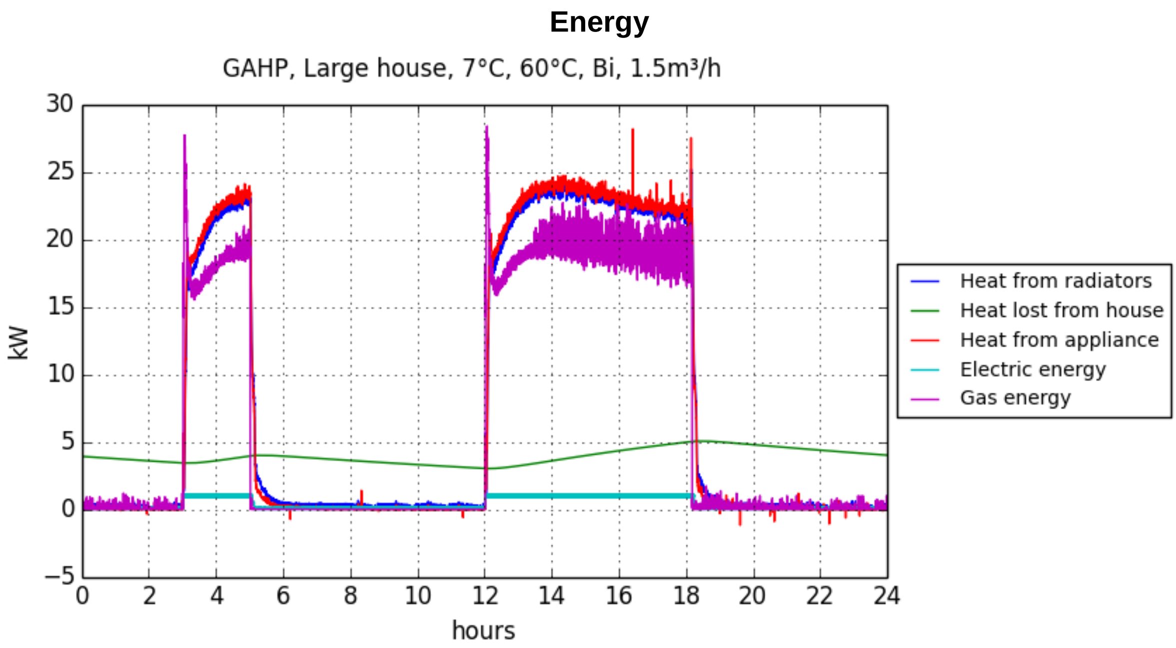
*[3] In addition to the original test regime, an extra test was undertaken with a different flow rate.

*[4] Test 134 was an extra test with the GAHP, this was undertaken bimodally to check the safety and running of the appliance, so therefore if the tests at 0°C under-heated the property, then the tests were repeated unimodally as per the test programme.

Extra tests were undertaken at higher flow rates to see if this had an effect on the test; because the instruction manual required a higher flow rate than previously used on the test rig. The effect on the efficiency of the GAHP was insignificant, although the heat output and gas input were slightly higher.

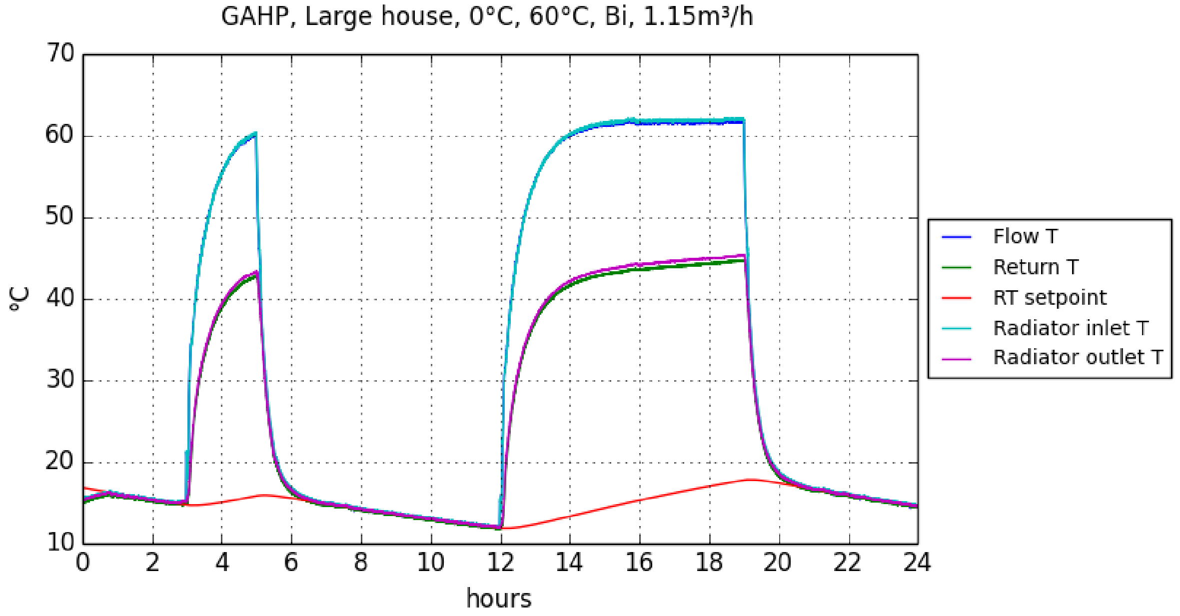
Test number 178



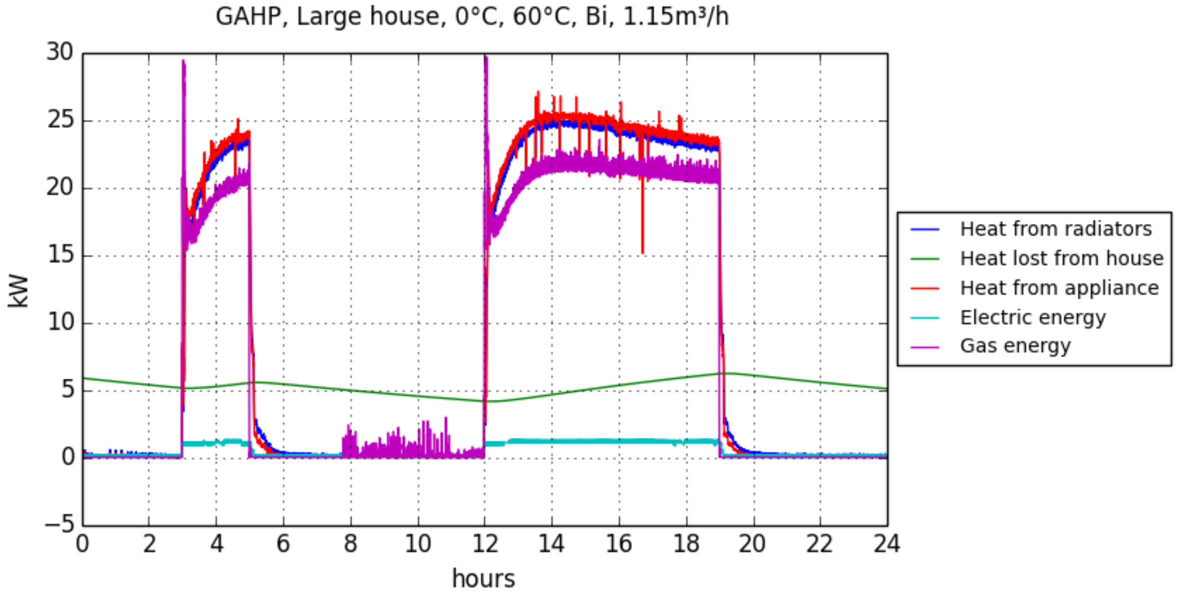


Test number 134

Temperatures

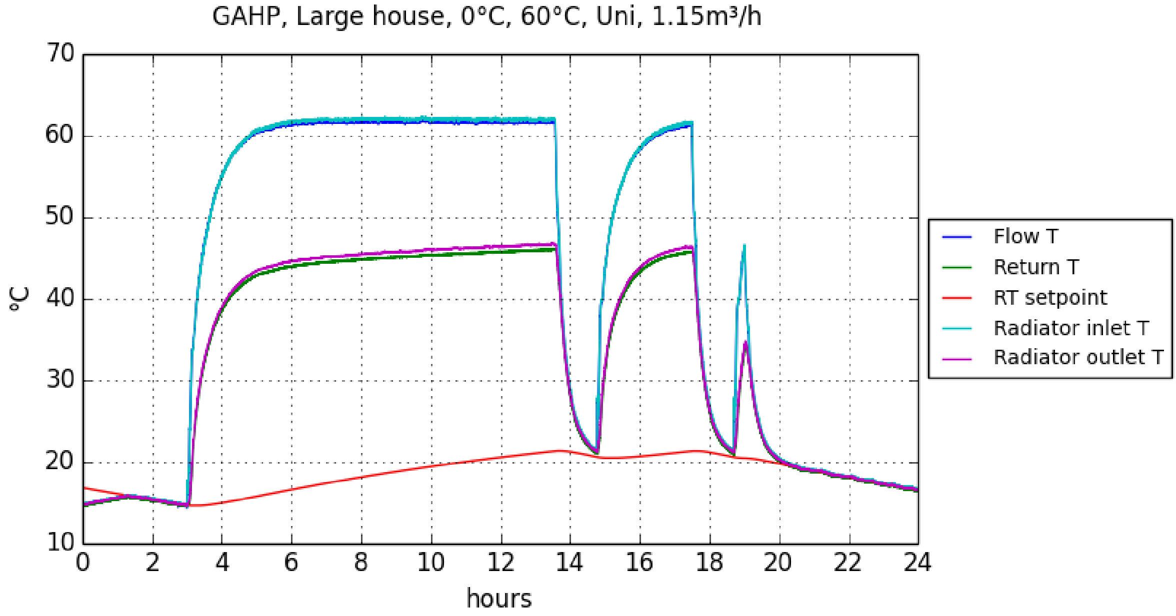


Energy

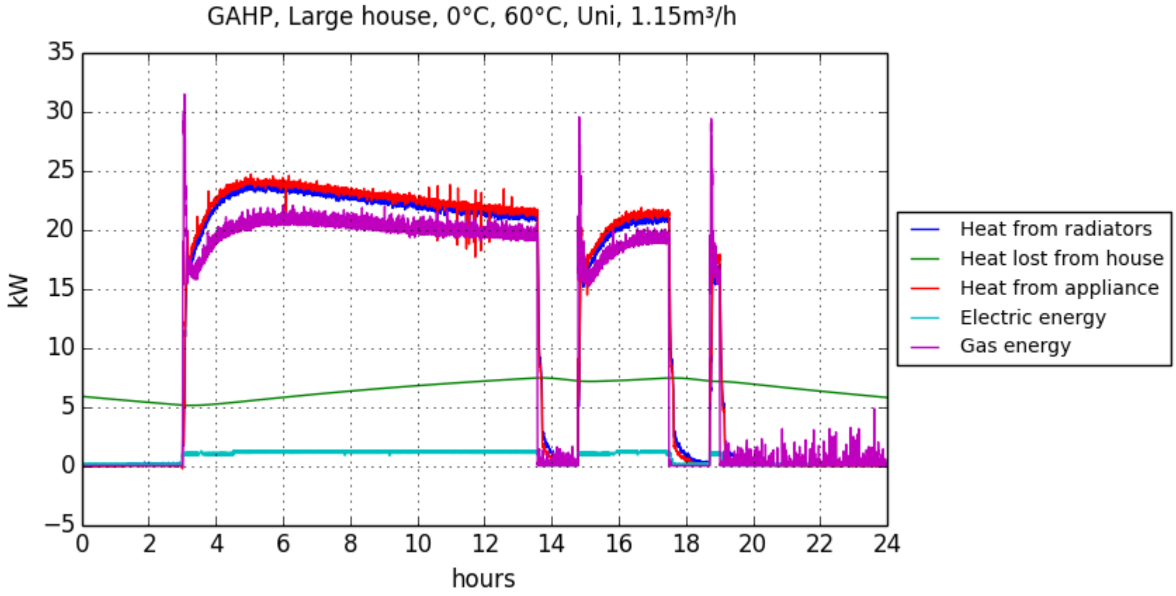


Test number 136

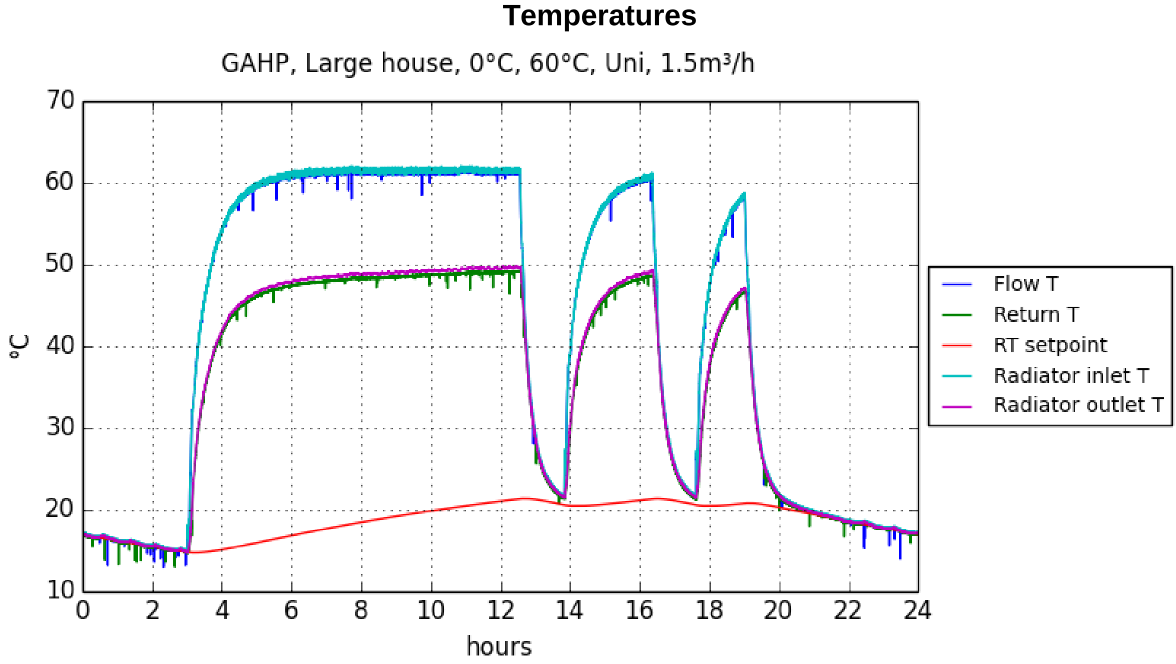
Temperatures

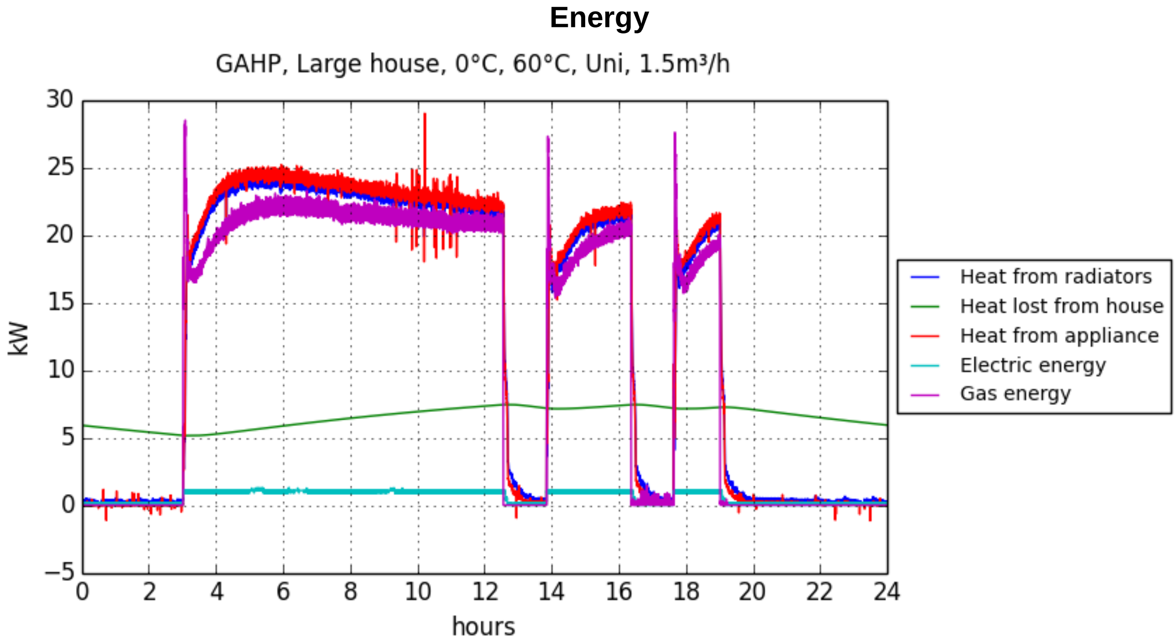


Energy

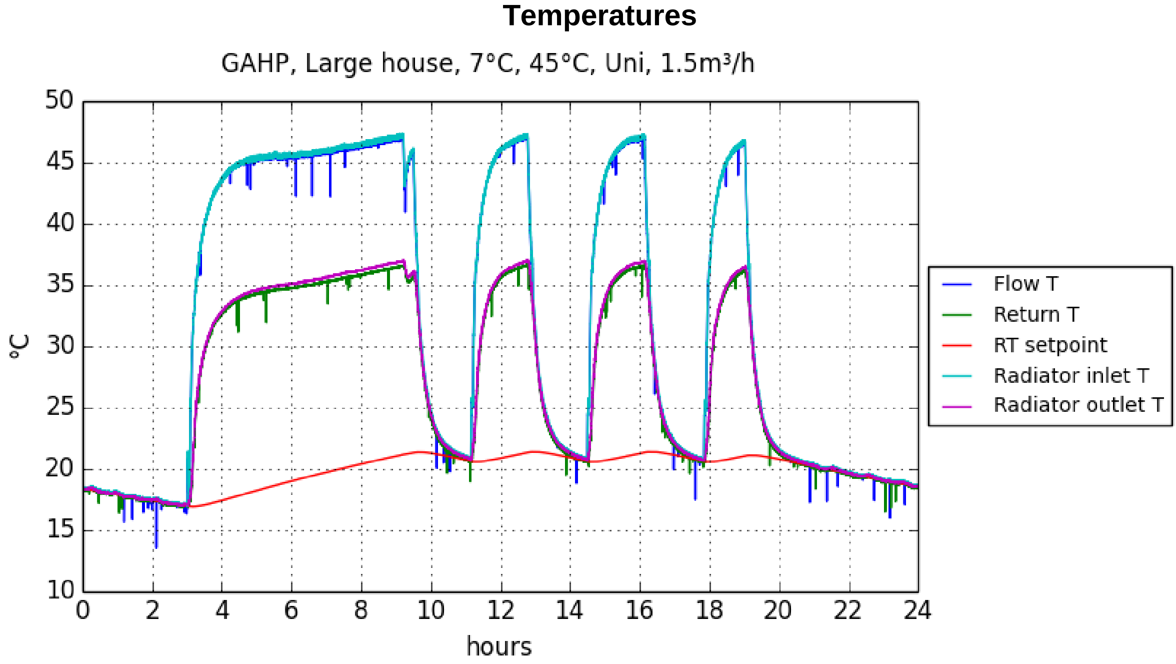


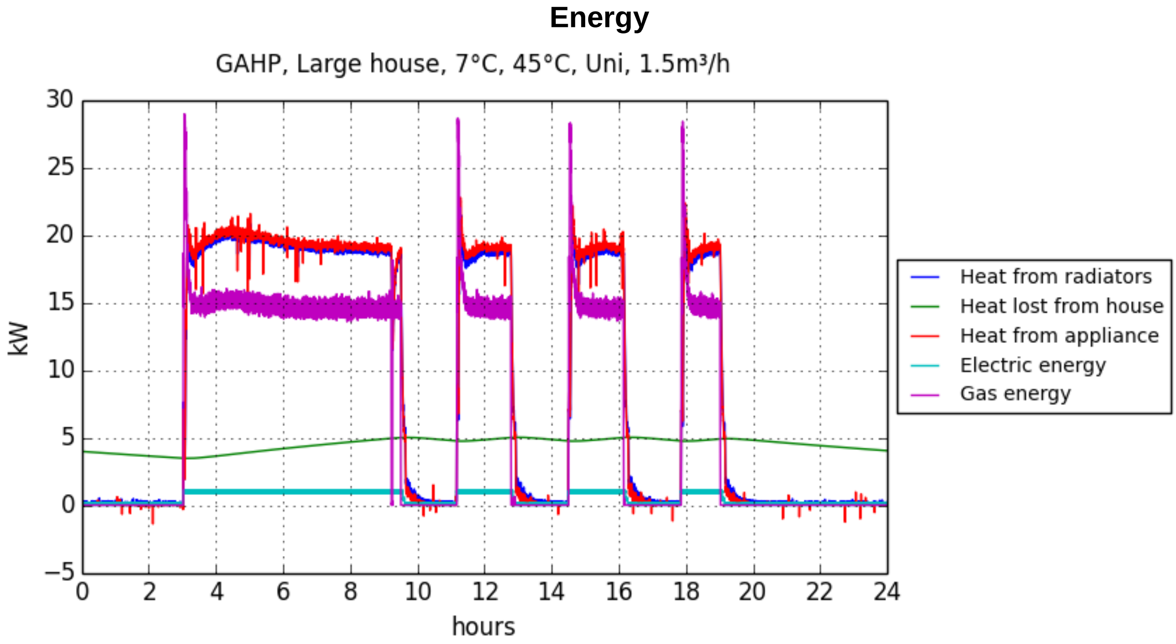
Test number 184



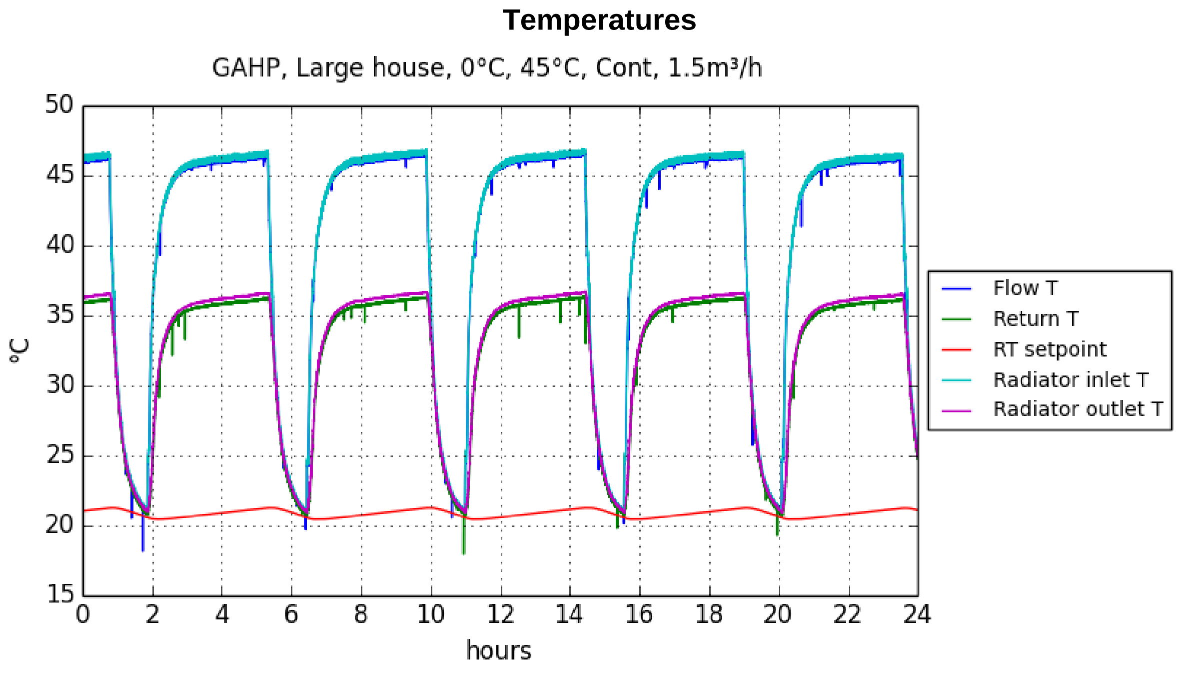


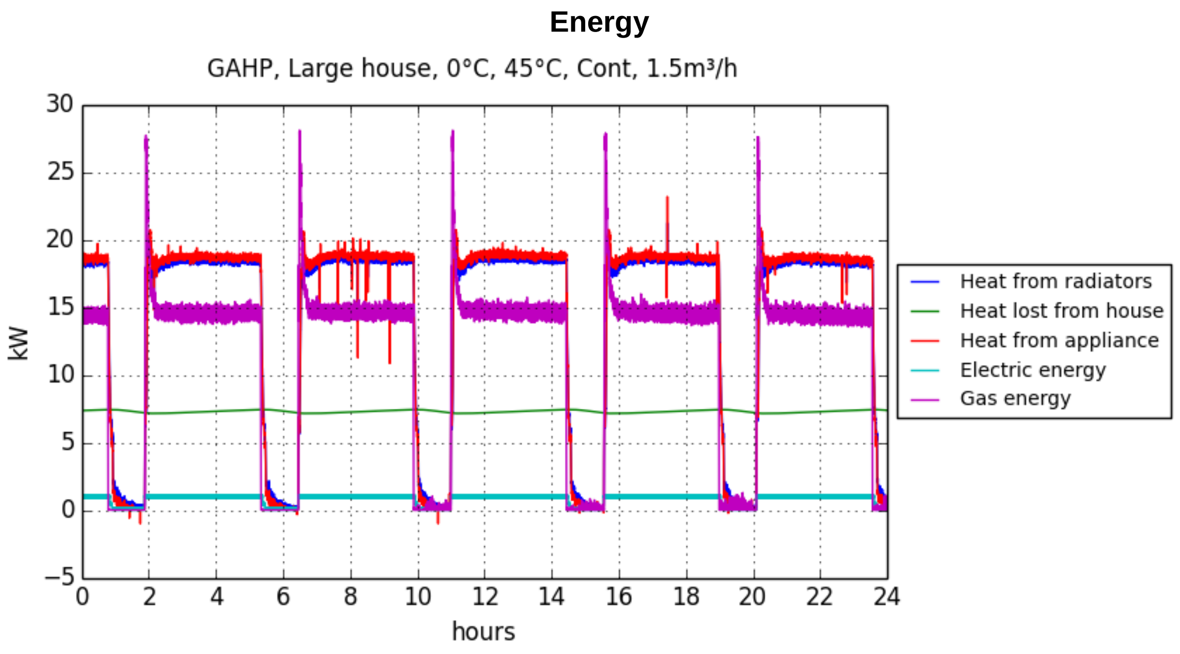
Test number 170





Test number 162





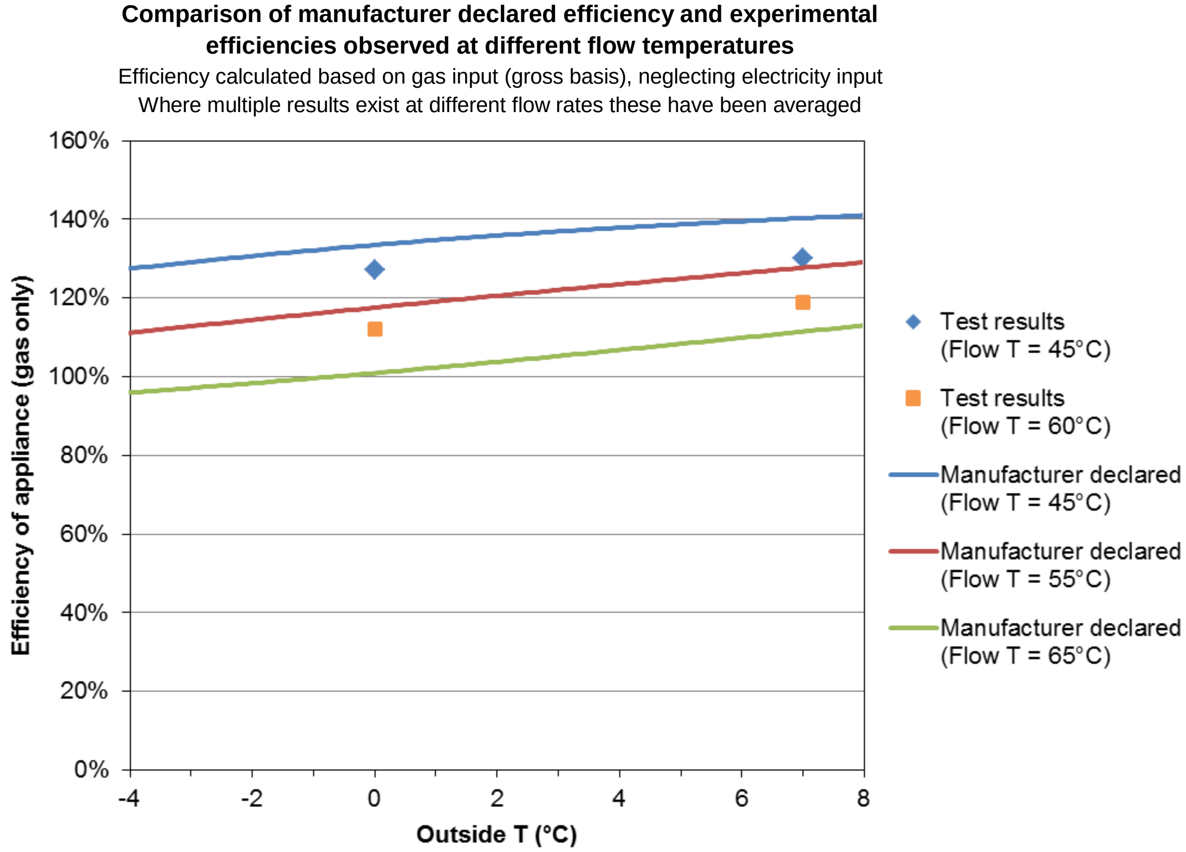
The GAHP typically operated in the gas input range 14-22kW. There was no evidence of cycling on water flow temperature. If the room temperature set point was reached then the system switched on/off with a period of around 4-5 hours.

The radiator water flow rate for the GAHP was limited to a maximum of 1500l/h compared to the recommended flow rate of 3000l/h, however the flow rate was higher than the minimum 1000l/h. The flow rate was increased from 1150 to 1500l/h during the test for one set of conditions (see tests 136 and 184), the effect on efficiency was insignificant.

The radiators were the limiting factor in the GAHP tests; at 14.9°C the internal temperature could not be judged as acceptable in the bimodal tests at 0°C.

The efficiency was higher at lower flow temperatures than at higher flow temperatures. The external temperature had less effect on the efficiency compared with an ASHP. The manufacturer declared efficiencies for the GAHP are compared with the experimentally determined efficiencies below.

The manufacturer declares efficiencies based on gas input (gross basis), so for comparison purposes electricity use has been excluded from these efficiencies. Including electricity would take on average 10% (expressed as percentage points) off these vales. This is an argument for requiring manufacturers of GAHP to report efficiency including electricity.



The efficiencies observed during testing at water flow temperatures of 60°C were consistent with the manufacturer's declared performance. At flow temperatures of 45°C, the efficiency did not increase as much as predicted by the manufacturer data.

One reason for this reduced performance could be the gap (as discussed in Section 2.1.1) between performance in laboratory testing (to a testing standard) and performance in the 'real world', and the associated lower efficiencies often observed there, due to the non-ideal conditions experienced by the appliance.

It could be also argued the unit was oversized for the house size used during testing, however this is a complex issue. There are advantages in using over-sized heat producers as they allow bimodal heating (which as demonstrated in Section 3.2 can save significant amounts of energy). By these criteria the unit was not unreasonably oversized when compared to standard UK practice.

Table 5 compares the GAHP heating this 700W/K house to the 28kW gas combi boiler heating the smaller 300W/K house (although in practice such boilers are usually down-rated as low as 18kW when operating in central heating mode[11]).

Table 5: Comparison of load factors for GAHP and gas boiler

		Large house GAHP	Small house Gas boiler
HLC	W/K	700	300
Average internal temp	C	19	19
Average outside temp	C	2*	2*
Average heat load	kW	11.9	5.1
Bimodal operating hours	hours/day	9	9
Property demand	kWh/day	286	122
Average heat output required	kW	31.7	13.6
Design output of appliance in CH mode	kW	36	18
Ratio of design output to heat demand		113%	132%

* Chosen as an arbitrary cold day where the householder might not have switched to unimodal or continuous heating.

The validity of this table can be demonstrated by comparing the similar unimodal operation of the gas boiler and GAHP at both 0°C external temperature and radiators at 60°C (tests 083 and 136) and 7°C external temperature and radiators at 45°C (tests 092 and 170).

The energy flow graphs of the GAHP during start-up are similar to those of the gas boiler, so it is suggested that the efficiency of the GAHP will be lower if the cycling is frequent, because of purge etc. The GAHP however was not observed to cycle on flow temperature in any of the test programmes and typical operating times were 2 hours on and 2 hours off. Such a control strategy is definitely beneficial.

The ability of a GAHP to provide large quantities of heat (like a boiler) is clearly advantageous to bimodal heating of large properties and thus they could be ideal for retrofitting into large and/or poorly insulted properties. There is however the complication that achieving higher efficiencies requires low or even better very low water flow temperatures. The latter necessitates underfloor heating or very large radiators, and anecdotally there is an issue with consumer resistance to radiators (which intrinsically must have high surface heat transfer coefficient and high thermal mass) that feel cold to the touch, i.e. are operating at below body heat[14].

4 Discussion

4.1 Difference between laboratory, dynamic rig and field data

The measured efficiencies on the dynamic test rig for the gas boiler are significantly higher than the seasonal efficiencies seen in field trials (which are typically 86±2%[9]) because:

- field trials include DHW production, generally at poor efficiencies of ~70 to 75%
- in a domestic property the gas boiler may not be correctly sized to the load and radiators
- this gas boiler had good modulation
- the water flow temperatures of 60°C and 45°C are significantly lower than the 70-80°C conventionally used in traditional radiator systems
- higher water return temperatures due to spill back

The ASHP efficiency is lower on the dynamic test rig than in laboratory field tests. This is partly due to the dynamic test rig requiring two pumps to achieve the flow rates expected. These pumps equate to 110W with the standard flow rates, and 190W for the higher flow rates. They run continuously no matter what the heating pattern. This has a significant impact on the efficiency of the ASHP, downgrading the efficiency by 4-10%. Other effects could be:

- higher water flow/return temperatures than employed in the standard – laboratory tests are undertaken at 35°C, the dynamic rig tests were undertaken at 45°C and higher
- effect of defrost

With the GAHP there is a significant discontinuity between the results observed here and those achieved in the EN tests at the lower emitter temperature. Interestingly, data from Kiwa Gastec in the Netherlands indicates efficiencies of 120% are typical for field installations of GAHP[15]. A few reasons for this could be:

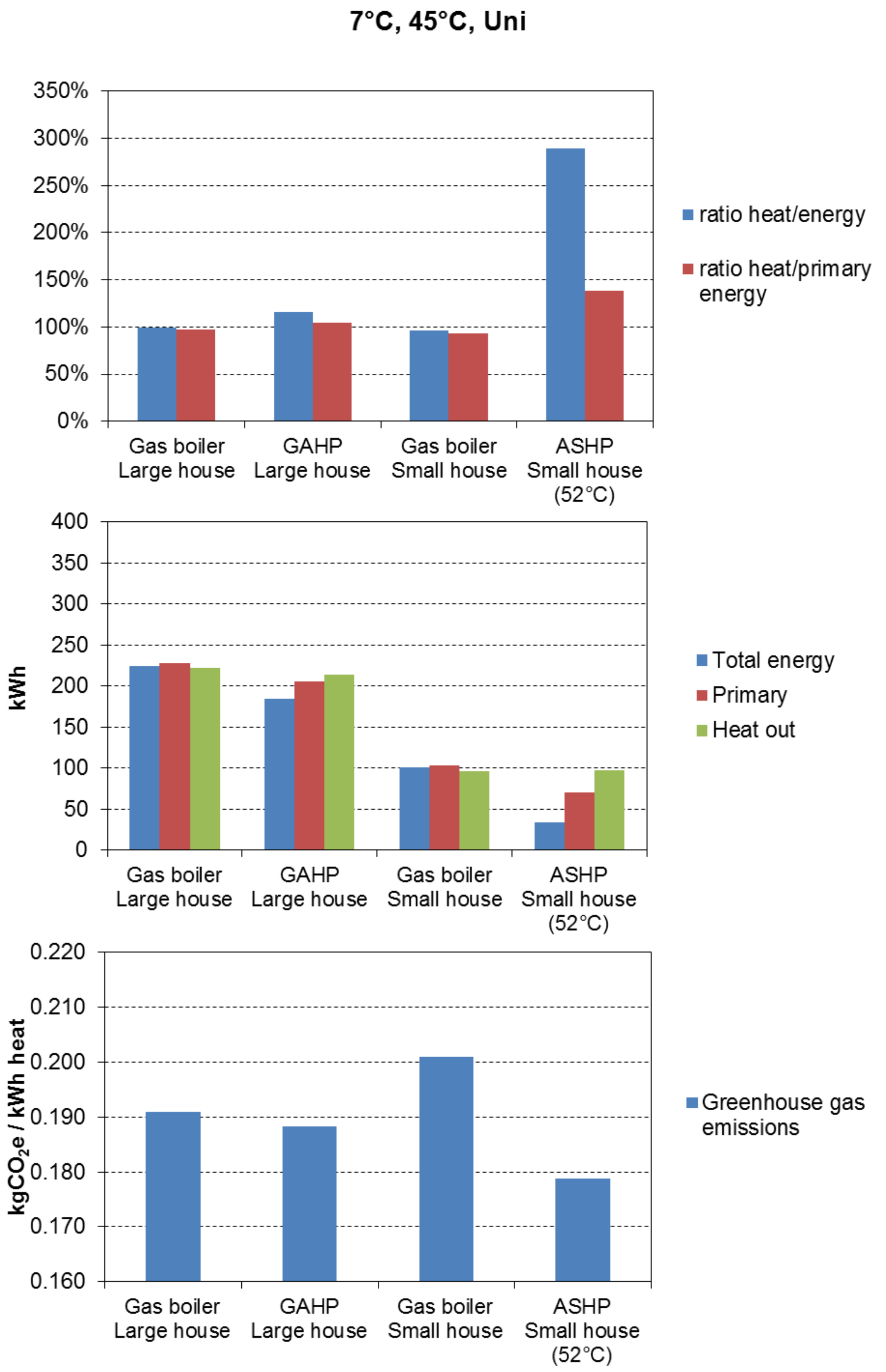
- the dynamic operation
- higher water flow/return temperatures than employed in the standard
- the pumps account for 2-4% of the difference in efficiency, depending on whether the field installation includes pumps
- effect of defrost

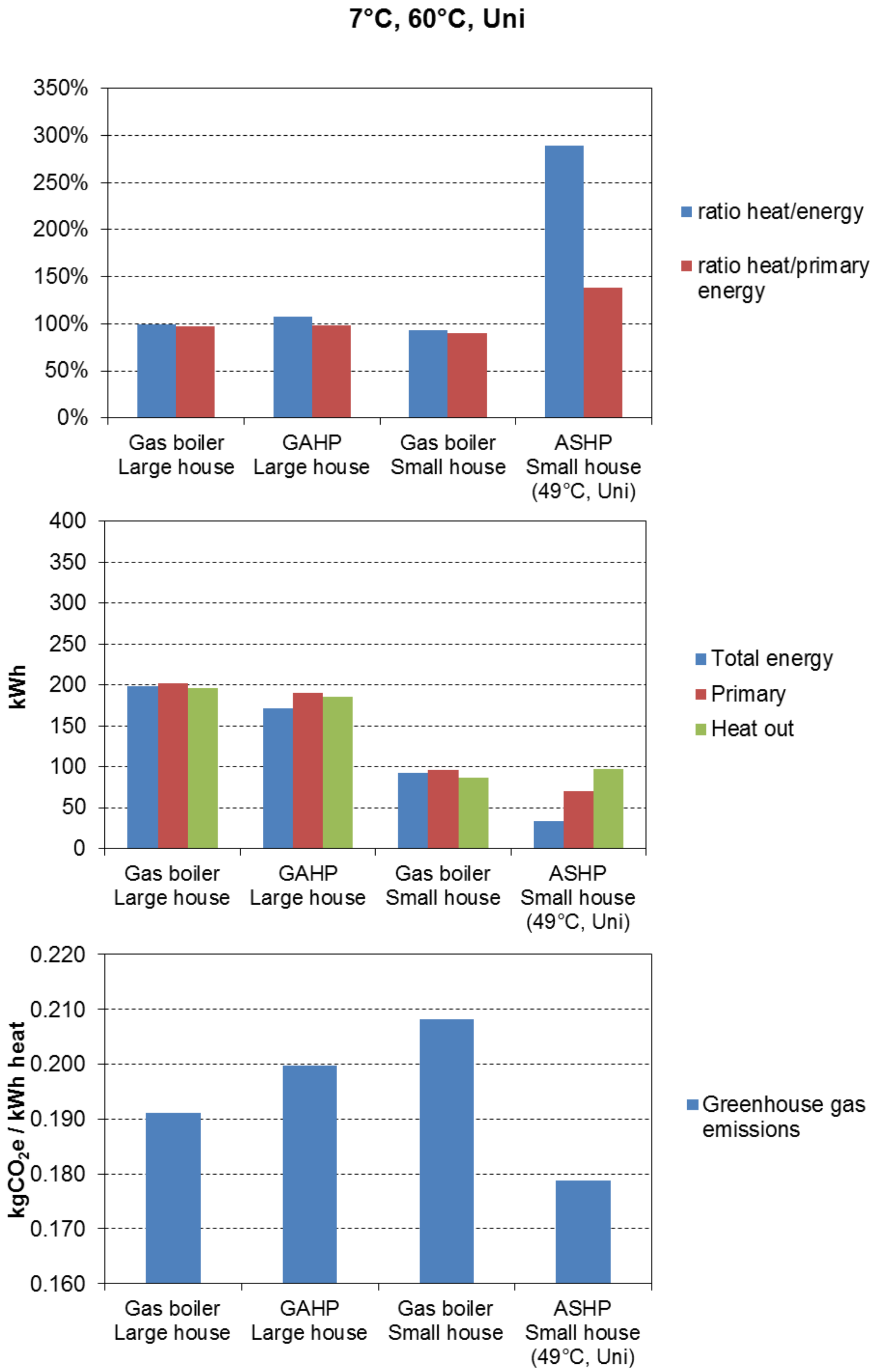
4.2 Primary Energy and Carbon Emissions

The primary energy (in kWh) has been calculated from the gas and electricity consumption, assuming electricity is supplied from a combined cycle gas turbine with an efficiency of 47.7%[1]. This is used to produce a heat to energy ratio (the efficiency) and a heat to primary energy ratio for each different set of conditions.

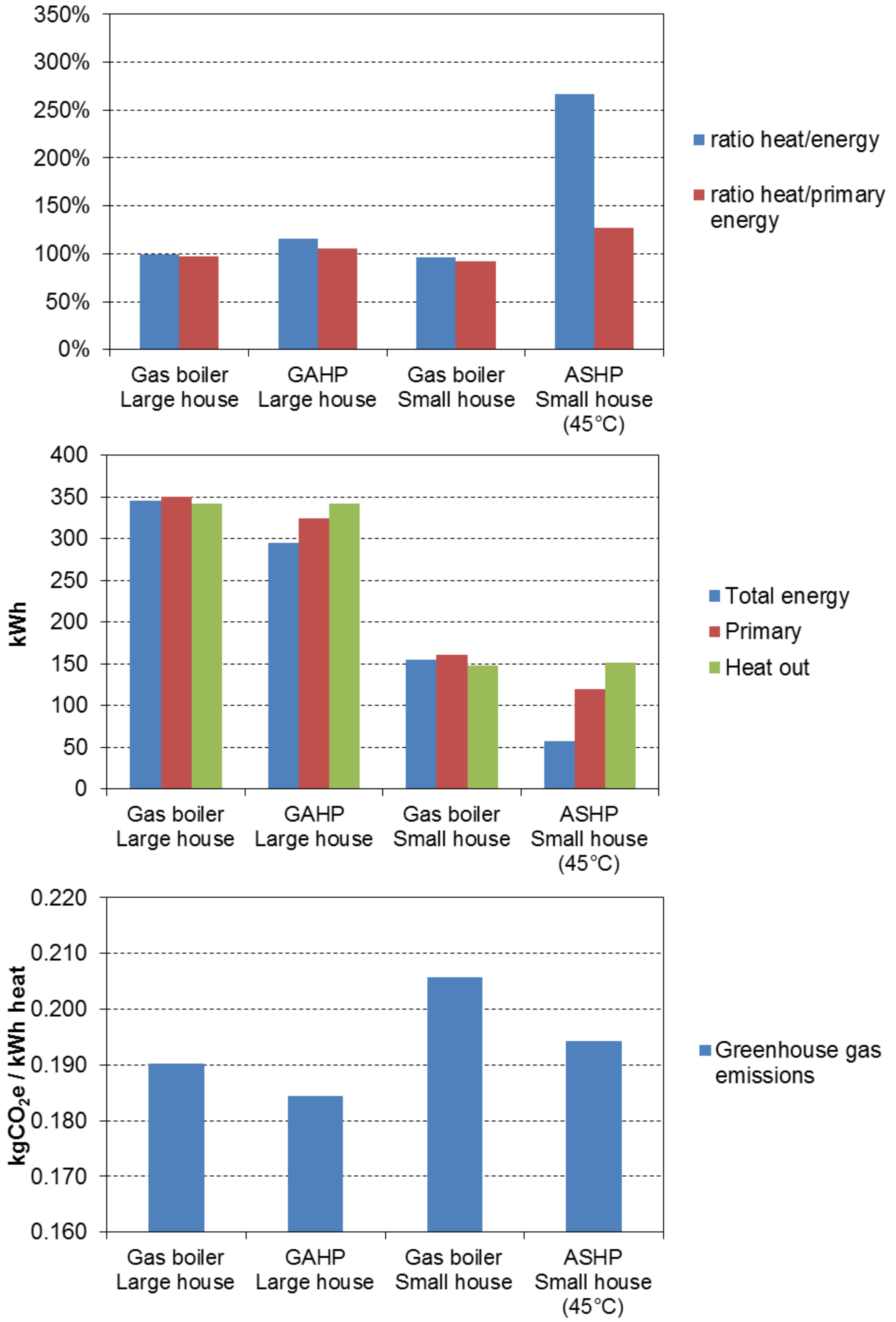
This assumes that all the electricity consumed is generated by combined cycle gas turbine which is the most efficient type of fossil fuel power station. With the current mix of coal generation in the UK, the primary energy consumption of the ASHP (and also the GAHP), may be higher.

The equivalent CO_2 emissions (per kWh of heat output) were also calculated, assuming emissions factors of 0.5173 $kgCO_2e/kWh$ for electricity and 0.1841 $kgCO_2e/kWh$ for gas[3].

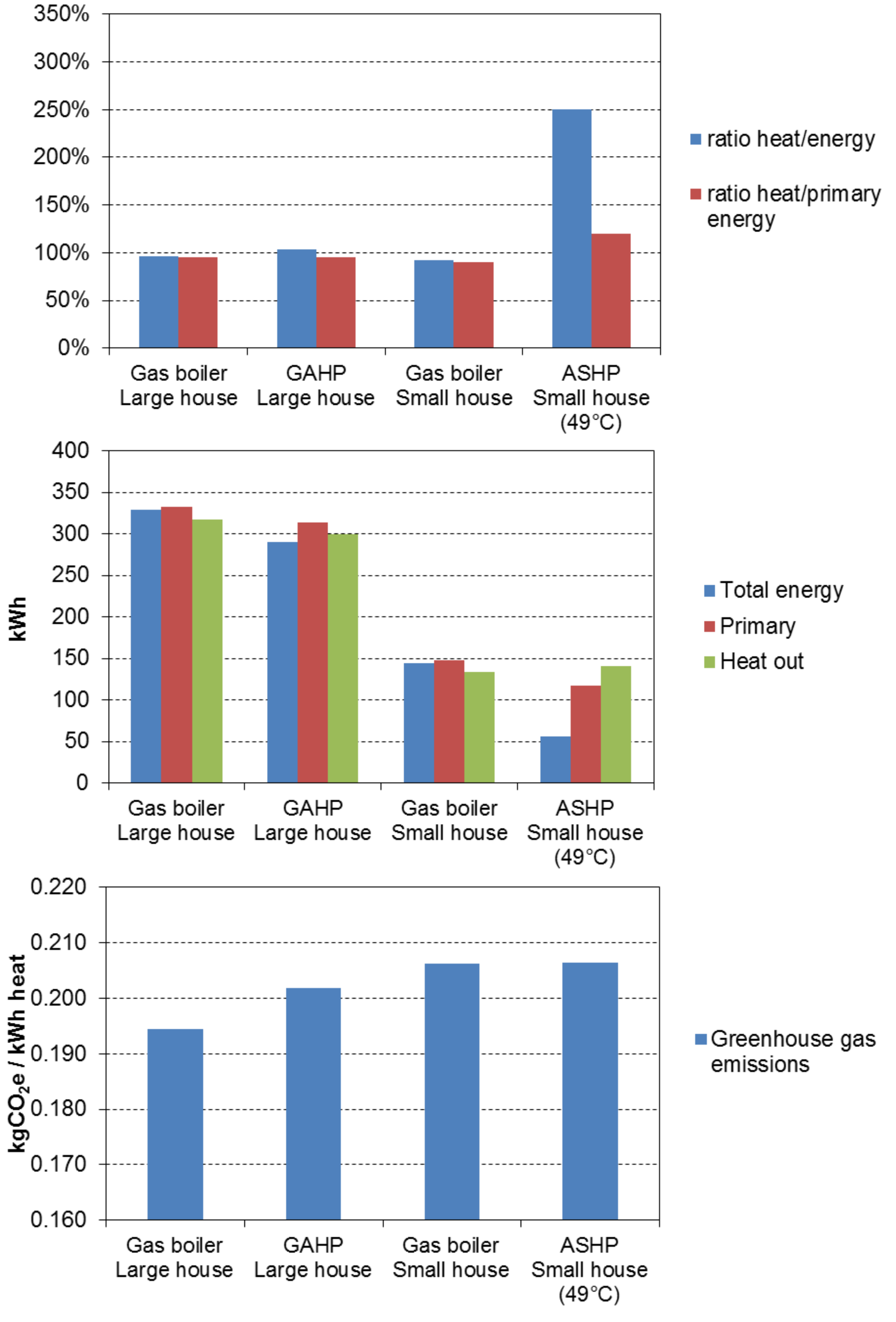

7°C, 45°C, Uni
350%
300%
250%
200%
150%
100%
50%
0%
ratio heat/energy
ratio heat/primary energy
Gas boiler Large house
GAHP Large house
Gas boiler Small house
ASHP Small house (52°C)
kWh
400
350
300
250
200
150
100
50
0
Total energy
Primary
Heat out
Gas boiler Large house
GAHP Large house
Gas boiler Small house
ASHP Small house (52°C)
kgCO2e / kWh heat
0.220
0.210
0.200
0.190
0.180
0.170
0.160
Greenhouse gas emissions
Gas boiler Large house
GAHP Large house
Gas boiler Small house
ASHP Small house (52°C)


7°C, 60°C, Uni
350%
300%
250%
200%
150%
100%
50%
0%
ratio heat/energy
ratio heat/primary energy
Gas boiler Large house
GAHP Large house
Gas boiler Small house
ASHP Small house (49°C, Uni)
kWh
400
350
300
250
200
150
100
50
0
Total energy
Primary
Heat out
Gas boiler Large house
GAHP Large house
Gas boiler Small house
ASHP Small house (49°C, Uni)
kgCO2e / kWh heat
0.220
0.210
0.200
0.190
0.180
0.170
0.160
Greenhouse gas emissions
Gas boiler Large house
GAHP Large house
Gas boiler Small house
ASHP Small house (49°C, Uni)

0°C, 45°C, Cont


350%
300%
250%
200%
150%
100%
50%
0%
Gas boiler Large house
GAHP Large house
Gas boiler Small house
ASHP Small house (45°C)
ratio heat/energy
ratio heat/primary energy
kWh
400
350
300
250
200
150
100
50
0
Total energy
Primary
Heat out
kgCO2e / kWh heat
0.220
0.210
0.200
0.190
0.180
0.170
0.160
Greenhouse gas emissions

0°C, 60°C, Uni


350%
300%
250%
200%
150%
100%
50%
0%
Gas boiler Large house
GAHP Large house
Gas boiler Small house
ASHP Small house (49°C)
ratio heat/energy
ratio heat/primary energy
kWh
400
350
300
250
200
150
100
50
0
Total energy
Primary
Heat out
kgCO2e / kWh heat
0.220
0.210
0.200
0.190
0.180
0.170
0.160
Greenhouse gas emissions

The following tables compare total carbon emissions to maintain a property at the declared average internal temperatures (shown in brackets) when the external temperatures are 0ºC and 7ºC. For comparison UK field trials show average internal temperatures in the range 17.7ºC [2].

	Daily carbon emissions ($kgCO_2e$/day) (Average internal temperature (°C))			
	Small house (300W/K)		Large house (700W/K)	
External temp 0°C	**Boiler**	**ASHP**	**Boiler**	**GAHP**
Bimodal Rads 60°C	N/T	N/T	N/T	N/T
Bimodal Rads 45°C	N/T	N/T	N/T	N/T
Unimodal Rads 60°C	27.5 (19.0)	29.0 (17.7)	61.7 (18.5)	60.6 (18.4)
Unimodal Rads 45°C	26.9 (18.9)	N/T	N/T	N/T
Continuous Rads 60°C	N/T	34.2 (20.8)	N/T	N/T
Continuous Rads 45°C	30.5 (20.9)	30.5 (20.8)	65.0 (20.9)	63.1 (20.8)
External temp 7°C	**Boiler**	**ASHP**	**Boiler**	**GAHP**
Bimodal Rads 60°C	17.9 (18.8)	N/T	37.5 (18.2)	37.1 (18.2)
Bimodal Rads 45°C	N/T	N/T	N/T	N/T
Unimodal Rads 60°C	20.0 (20.3)	17.4 (19.5)	N/T	N/T
Unimodal Rads 45°C	19.4 (20.0)	N/T	42.4 (19.8)	40.2 (19.8)
Continuous Rads 60°C	N/T	19.3 (20.9)	N/T	N/T
Continuous Rads 45°C	N/T	16.4 (20.9)	N/T	N/T

Key: N/T = Not tested as would not be realistic of operation of the appliance in the field.
Reasons for this may include: there would be insufficient heat output from the appliance to meet the heat demand of the house, the radiators would be too small to deliver sufficient energy to the house, or the appliance would cycle too frequently.

The equivalent CO_2 emissions were calculated, assuming emissions factors of 0.5173 $kgCO_2e$/kWh for electricity and 0.1841 $kgCO_2e$/kWh for gas[16]. The ASHP could not achieve the 60°C radiator temperatures. More detailed notes are given in the results.

Inspection of the results shows the extreme complexity of the values with both bimodal operation and lower radiator temperatures lowering emissions, but in so doing making comparison between heating systems very difficult.

The report highlights the need to consider 5 factors when assessing the performance of a heating system:

1. The ability of the system to operate bimodally, unimodally or continuously whilst giving acceptable internal temperatures
2. System water temperature (especially return)
3. The instantaneous and average efficiency of the appliance in terms of both gas and electricity
4. Ability to respond to external temperature
5. The carbon emissions of the above operating regime

To give undue weight to any one of these factors (for example appliance efficiency) is likely to only yield part of the picture.

In the large house the GAHP used slightly less primary energy than the gas boiler to give the same notional comfort level. The electricity use of the GAHP was higher than the electricity use of the gas boiler especially once both circulating pumps were added in. On the continuous test, the GAHP used 26kWh of electricity compared with 4kWh of electricity used by the gas boiler, but the overall efficiency of the system was 114% with the GAHP compared with 99% with the boiler. In terms of primary energy use, the ratio of heat to primary energy was 106% with the GAHP compared with 98% with the gas boiler, and the carbon emissions were 0.184kgCO_2e/kWh with the GAHP compared with 0.190kgCO_2e/kWh with the gas boiler.

Both the GAHP and gas boiler in the large house were limited by the radiators in the 7°C bimodal test. The room temperature averaged 18.2°C for this test; the gas boiler and GAHP had similar outputs from the radiators to achieve this, however the GAHP was more efficient than the gas boiler.

In the large house, the GAHP had thermal efficiencies between 8-17 percentage points higher (13 percentage points higher on average) than the gas boiler. In terms of carbon emissions the reduction was only 1-5% (3% on average). The reason for the small reduction in carbon emissions is the proportionally higher carbon footprint of electricity.

For the large house the ASHP was not tested as it had insufficient output to match the property. In reality, a number of ASHP units would likely be used in combination to fully satisfy the heat demand, although standard domestic wiring might be insufficient to meet the electrical requirements of this set-up.

4.3 Timed heating

During bimodal heating the property is heated morning and evening as is typical in the UK. House temperatures are limited either by radiator area and/or heating appliance output. With an external temperature of 7°C the house does not reach the set point temperature in the morning. This is typical and is consistent with previous laboratory tests[12]. The set up (i.e. gas boiler, radiators and time clock settings) maintains a mean internal temperature above 18.2°C throughout the day. This is typical when compared to that seen in real properties[9].

In the small house boiler test, continuous operation used 8% more gas than unimodal at 45°C and 5% more gas than unimodal at 60°C.

This demonstrates that:

- Switching the gas boiler off for 15 hours/day (i.e. bimodal operation) makes worthwhile savings in daily energy use, if the property can still be comfortably lived in.
- Operating the gas boiler in the small house at 45°C rather than 60°C makes 4% difference to gas demand and efficiency.
- Daily gas use is dominated by average house temperature and average gas boiler efficiency but the latter (on a modern condensing gas boiler) is constrained (for central heating production) in a relatively narrow range around 90 to 95%.

In the case of the smaller house, the balance of carbon emissions between the gas boiler and the ASHP becomes fine with the ASHP showing an advantage at 7°C, and the gas boiler an advantage at 0°C. However both are dependent upon radiator temperature – with radiators designed at 45°C (i.e. a 3.1 oversize factor on their normal rating) and an external temperature of 7°C, the ASHP carbon saving does become more significant – up to 15%.

5 Conclusions

The GAHP was compared against a broadly similar sized condensing gas boiler; the same gas boiler was used for comparisons with the ASHP as this would represent the common situation of a condensing combination gas boiler, where the output rating is determined by the instantaneous hot water demand rather than the space heating demand.

Compared with ASHPs, GAHPs have the advantage of being able to deliver heat in large quantities and at higher temperatures, which may allow installations in existing installations with fewer modifications to the property. However, truly domestic scale GAHPs are still in development. The unit tested here might have been better suited to very large houses or commercial applications, although strictly the GAHP was no more oversized than the typical gas combi boiler in a typical property.

All of the systems have to be viewed holistically. Just measuring efficiency is not really meaningful. This insight explains the widespread differences in energy consumption between apparently similar properties.

This work highlights the fact that using different heating patterns with different appliances can markedly affect both the reported efficiency and the actual energy used. A higher efficiency for the appliance may not save primary energy, if the methodology used to obtain the high efficiency results in the building remaining at a higher average temperature and thus using more primary energy.

In terms of actual energy used and primary energy used, high quality, well installed ASHPs show themselves to be an effective method of reducing energy use and carbon emissions in central heating applications with primary energy savings over a the gas combi of up to 20% at 0°C with radiators at 60°C, and rising to 32% at 7°C with radiators at 45°C, over the scenarios studied. It should be noted however that in conjunction with these savings, there may be a change in the average internal temperature of the house. Further changes may also be required such as the installation of additional radiators to enable lower flow and return temperatures to be used. This may result in changes to the level of comfort experienced by the householder. The large scale introduction of this technology is also limited by both grid capacity and installed cost.

In the interim GAHPs should have a role to play in saving energy and balancing the demand between gas and electric over the coming years with primary energy savings over a the gas combi of up to 6% at 0°C with radiators at 60°C, and rising to 10% with radiators at 7°C with radiators at 45°C, over the scenarios studied. Design, installation and control have been shown to be important and this should also be considered. Further development of GAHPs should result in improved performance as the technology matures and also optimisation for UK conditions (climate and usage patterns) could bring benefits.

The data shows that there is still much to be understood about heat sources, emitters and optimum operating regime.

6 Further work

There are currently no small output GAHPs available in the UK so the technology could not be tested in the smaller property, but the data would indicate that there should be primary energy savings over the gas boiler. This would combine the potential benefits of rapid heat up with higher efficiencies than gas boilers using the same infrastructure that is currently established in the UK. They could even be regarded as merely a further step in the long term development of the gas boiler from traditional open-flued, to high efficiency fan flued, to fan flued condensing boiler and eventually to gas-fired heat pump.

This work has not touched upon the effect of radiative vs convective heat in relation to householder comfort. Anecdotes and Dutch data[17] provide some evidence that higher temperature emitters permit lower air temperatures for the same level of “comfort”. This may explain why some householders find bimodal heating (when the radiators are always hotter morning and evening) more comfortable than might be expected.

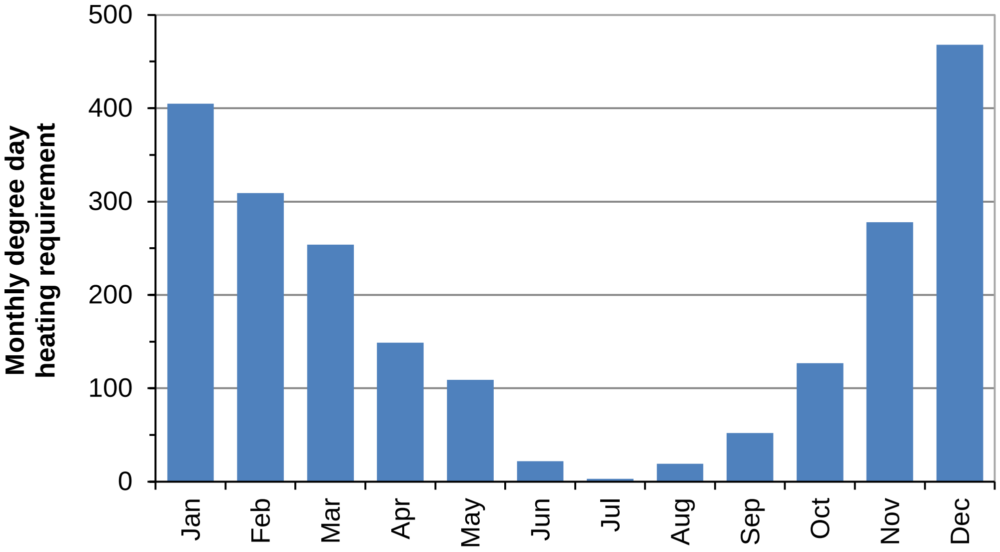
It should be noted that this work also excluded the effect of DHW production. In general, DHW is produced and supplied at relatively high temperatures (60°C to 65°C). Requiring higher temperatures is likely to increase the primary energy use of all three technologies. It is anticipated that the most affected technology would be the ASHP, due to the high flow temperatures required for DHW which are often unachievable without supplementary heaters. The GAHP has not been tested for DHW production so this cannot be compared to the gas boiler.

This work modelled standard radiators; underfloor heating is conventionally associated with continuous heating, although underfloor heating systems can use a night set back. The lower flow temperatures required by underfloor heating could increase efficiencies but may be significantly affected by DHW production. More work is required on the basis of primary energy per property per year. There are also issues with the relative responsiveness of radiators and underfloor heating in concrete screed.

When evaluating the relevance of laboratory testing standard results, it is useful to consider the actual load factor experienced by an appliance in the UK. This load factor can be calculated from the monthly degree day heating* requirement, shown in the figure below

* Degree days heating are a measure of the deficit between the average daily outside temperature and a ‘base temperature’ (below which the property requires no heating). More information is available at: www.vesma.com/ddd

Typical UK monthly degree day heating requirement[18]



Design degree day values are typically 700 to 750 DDH in the UK. It can be seen from the figure above that boiler load factors can be less than 10% for 4 months of the year, and less than 30% for around 8 months of the year. Therefore it is vital that any technology new to the UK can operate efficiently at low load or when only called upon to operate very intermittently.

This is why PAS67[4], the UK test protocol for mCHP units, contains a requirement to test at 10% daily load (i.e. 2.4 hours/day). A very similar approach is developed within the new BSEN14825:2013. (Air conditioners, and heat pumps... testing and rating at part load conditions and calculation of seasonal performance). Whilst always assuming continuous heating this allocates heating and cooling into temperature bins and then sums these to produce an annual performance (termed a seasonal COP or SCOP). This standard does endeavour to model the effect of load factor, but many of the measurements are non mandatary so how accurately the results reflect reality is still to be proven. (It is noted that that the GAHP tested is promoted as a base load unit, although this will tend to limit its application, as many large heating systems which might incorporate such base load appliances tend to operate with water temperatures above the 45°C necessary to obtain the highest efficiencies.)

This whole area could benefit from further research and perhaps consideration of the introduction of a 24 hour test programme that would test heat pumps at 100%, 30% and 10% of thermal rating to report their response to low loads. Although at first sight complex, PAS67 does have the advantage of offering the manufacturer a range of recommended operating regimes, e.g. bimodal, unimodal and continuous.

Many mCHP manufacturers have found that investigating performance under these conditions yields considerable improvements in appliance performance; it has also saved them from the poor publicity likely to arise from mCHP installations that operate disproportionately poorly at low load. There could be parallels with GAHPs here, as both technologies have to establish equilibrium of their working fluids to achieve optimum output.

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