Detailed analysis from the second phase of the Energy Saving Trust's heat pump field trial

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Preface

The Energy Saving Trust monitored 83 heat pumps in residential properties across Great Britain from April 2009 to March 2010. Findings from Phase I of this project were published in a report entitled "Detailed Analysis from the First Phase of the Energy Saving Trust's Heat Pump Field Trial - Evidence to Support the Revision of the MCS Installer Standard MIS 3005 Issue 3.1" [1]. The report examined a number of the heat pump installations in detail, paying particular attention to the factors that influence system performance. As a result of some of the analysis presented in the Phase I report, the Microgeneration Certification Scheme (MCS) standards for heat pump installation have been updated [2].

38 of the heat pumps were selected for interventions to improve their performance. Interventions ranged from major (swapping an over or under-sized heat pump), medium (changing radiators, adding a buffer tank, replacing circulating pumps with variable speed DC pumps) or minor (changes to controls, refilling the ground loop, adding insulation). 6 new heat pump systems were added to the sample and all were monitored from April 2011 to March 2012. This report presents the results.

Aimed primarily at heat pump manufacturers, installers and training and certification bodies, this report is specialist in nature. It will also be of interest to academics, building services engineers and low-carbon heating consultants.

Section 1 presents the sites and the interventions made.

Section 2 presents a description of system boundaries, as used in this study and by the EU RES Directive, the RHI and the RHPP. It also presents the monitoring schematics.

Section 3 presents histograms of temperature-corrected system efficiencies from Phases I and II as well as space and water heating efficiencies for the sites in Phase II.

Sections 4-7 present case studies.

Section 8 presents conclusions

Section 9 presents recommendations.

Summary

The Energy Saving Trust (EST) monitored 83 heat pumps in residential properties across Great Britain from April 2009 to April 2010.

The sample included a large number (44) of site permutations, broadly representative of the market at the time of commissioning the project, and included the following installation types:

- air-source and ground-source heat pumps
- heat pumps installed in private and social housing properties
- heat pumps installed in new-build and retrofit properties
- heat pumps providing heating only
- heat pumps providing heating and hot water
- heat pumps installed with different heat delivery systems: under-floor heating and/or radiators
- systems combined with solar water heating
- grant funded through the Low Carbon Buildings Programme and the Scottish Communities and Householder Renewables Initiative.

The sample was limited to heat pumps in residential properties only. Fifteen manufacturers' heat pumps were included in the trial. The results from this first phase were published in DECC's report "Detailed Analysis of the First Phase of the Energy Saving Trust's Heat Pump Field Trials" in April 2011.

38 heat pumps were selected for interventions to improve performance. The selection process was determined by:

- Identification of the need for an intervention or interventions
- Willingness of the manufacturer to carry out the intervention(s)
- Willingness of the householder to participate in a further year of monitoring.

A further 6 sites were added to the sample.

In a significant number of cases, additional monitoring was undertaken.

The report should be read in conjunction with other analysis from the field trial, namely:

- analysis of data from the first phase of the Energy Saving Trust Heat Pump Field Trial [1]
- analysis of glycol samples from a selection of ground-source heat pumps in the trial [3]
- revised guidance for the design and installation of heat pump systems, MIS 3005 Issue 3.1, Microgeneration Certification Scheme, February 2012 [2]
- test house investigations of the effect of cycling on heat pump performance [4]
- modelling of the effect of cycling on the performance of ground-source heat pumps [5]
- laboratory tests to investigate of the interaction between hot water cylinders, buffer tanks and heat pumps [6].

Funding and Support: Acknowledgements

Phase I of this project was developed by the Energy Saving Trust and delivered with funding from a wide range of stakeholders including the UK's main energy suppliers: EDF Energy, NPower, British Gas, Scottish Power, Scottish & Southern Energy, E.On UK, and NIE Energy; the Scottish Government; the Department of Energy and Climate Change; the North West Regional Development Agency; and heat pump manufacturers and installers including: Danfoss UK, NIBE, Mitsubishi Electric, Earth Energy, Worcester Bosch and Baxi Group. These funders were all represented on the project's advisory group and were influential in the trial's development and site selection. They have also provided technical input and oversight and input into the data collection methodology. DECC and the Energy Saving Trust are most grateful for their funding and significant in-kind support, without which the first phase of this project could not have been completed.

Phase II of the project was funded by The Department of Energy and Climate Change, The Scottish Government, the Energy Technologies Institute, RWE nPower, EDF Energy, Scottish & Southern Energy, E.On UK, NIE Energy, British Gas, Scottish Power, Danfoss, NIBE and Mitsubishi. Additionally, several manufacturers contributed considerable in-kind support (undertaking modifications to heat pump systems and assisting in interpreting the data). These included: Calorex, Dimplex, Heat King, Ice Energy, IVT, Mitsubishi and NIBE.

This report has been produced after a successful period of analysis and industry engagement. The field trial project team would like to thank all those who have contributed to extracting useful information from the data, particularly those manufacturers who have carefully examined, challenged and subsequently used the data they have been presented with (and openly shared their own data) to improve the understanding of the team. DECC would also like to thank the Energy Saving Trust, and its contractors Kiwa Gastec at CRE and EA Technology for many hours of painstaking work.

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1. Site Selection and Installation Procedure

This section describes the selection of the sites investigated in Phase II of the trials and the interventions carried out to improve performance.

1.1. Site Selection

The original sample of 83 properties monitored in Phase I was selected by the Energy Saving Trust.

38 of these systems were selected for interventions and further analysis. The selection process was determined by:

- Identification of the need for an intervention or interventions
- Willingness of the manufacturer to carry out the intervention(s)
- Willingness of the householder to participate in a further year of monitoring.

The systems covered a wide range of configurations:

- Air and ground-source
- With standard radiators, fan-assisted radiators and underfloor heating
- With and without provision of domestic hot water
- Integrated and external domestic hot water tanks

A further 6 sites were added to the sample. Table 1 shows the configurations of the sites in Phase II.

	Radiators		Underfloor		Underfloor & Radiators	Total
	No domestic hot water	Domestic hot water	No domestic hot water	Domestic hot water	Domestic hot water	
Air-source	3	12	0	2	0	**17**
Ground-source	0	21	3	2	1	**27**
Total	**3**	**33**	**3**	**4**	**1**	**44**

Table 1: Configurations of the 44 sites in Phase II of the trials

The most common system configuration was a ground-source heat pump, supplying radiators and domestic hot water (21 cases), followed by an air-source heat pump supplying radiators and domestic hot water (12 cases).

1.2. Interventions

A range of interventions were made. These have been classified as major, medium and minor, see Table 2. In broad terms, major operations required input from a heat pump expert, medium ones could be carried out by a plumber, and minor ones consisted of changes to controls or a general service.

Major	Medium	Minor	No change	New Sites
Heat pumps replaced (according to manufacturers' recommendations, not necessarily compliant with MCS MIS 3005 issue 3.1 guidance)	Re-filling ground loop	Extra insulation (to building or pipes)		
Reduce area heated by heat pump	Installation of a buffer tank	Controls		
Repair leak to ground loop	Installation of a new hot water tank	Disabling auxiliary heater		
Recharging refrigerant	Connection of shower to heat pump circuit			
	New radiators			
	New circulation pumps			
	Voltage optimiser			
	Flap valve mended/replaced.			
	Changing manifolds			
12	9	11	6	6

Table 2: Interventions carried out prior to Phase II

The six new sites were all air-source and were designed and installed according to the requirements of the new MCS MIS 3005 Issue 3.1 standards. The remaining heat pumps were installed prior to these standards and so are not necessarily compliant with them. Nine of the heat pumps were replaced (as a "Major" intervention); it is important to note that these replacement heat pumps were designed and sized according to the manufacturers' procedures at the time (2010) and so are not necessarily compliant with the new MCS standards.

Most of the modifications are self-evident, but the voltage optimiser requires some explanation. The voltage optimiser selected is designed to lower the input voltage to 220V. There are two factors to consider in terms of whether this will result in any energy savings:

1. Whether 220V is indeed lower (on average) than the supply voltage to the property (in the UK, the acceptable range is 216.2-253 V)

2. Whether the motor is inefficient at voltages above 220V.

With an efficient motor, the effect of reducing the voltage will be negligible. However, with an inefficient motor, lower voltages will reduce iron losses within the motor and hence achieve savings.

Irrespective of motor efficiency, the lower voltage will slow the motor slightly and hence the compressor duty will also be slightly reduced. However, unless the compressor is running continuously at its maximum capacity, this will not affect heat output over time (it will just run slightly longer with the voltage optimiser).

Table 3 lists the sites retained for monitoring in the second phase and the interventions made.

			Major				Medium									Minor					No change
Site	Air/ground source	Heat emit	New heat pump	Reduce area heated by heat pump	Repair ground loop leak	Recharge refrigerant	Re-filling ground loop	Add or swap a buffer tank	New hot water tank	connect shower to heat pump	New radiators	New circulation pumps	Voltage optimiser	Flap valve mended/replaced,	Changing manifolds	Balance radiators	Controls	Disabling auxiliary heater	Adding insulation to pipes,	disabling surplus pumps	
41[illegible]	ASHP	Underfloor	x					1												1	
477	GSHP	Underfloor		x																	
422	ASHP	Radiators	x					1				1				1					
444	ASHP	Radiators	x														1				
473	ASHP	Radiators	x																		
41[illegible]	GSHP	Radiators	x				1	1													
427	GSHP	Radiators			x	x	1								1						
41[illegible]	GSHP	Underfloor/Rad	x														1				
41[illegible]	GSHP	Radiators	x					1		1						1					
4[illegible]	GSHP	Radiators	x																1		
423	ASHP	Radiators	x					1				1				1					
4[illegible]7	GSHP	Radiators	x					1	1		1										
41[illegible]	GSHP	Underfloor										x						1			
433	GSHP	Radiators										x	x				1				
43[illegible]	GSHP	Radiators										x					1				
432	GSHP	Radiators										x					1				
4[illegible]	GSHP	Radiators					x	x				x							1		
4[illegible]	ASHP	Radiators						x				x									
4[illegible]	GSHP	Radiators												x							
437	GSHP	Radiators										x	x				1				
434	GSHP	Radiators										x									
412	GSHP	Radiators															x				
4[illegible]	GSHP	Radiators															x				
435	GSHP	Radiators															x				
442	ASHP	Radiators															x				
4[illegible]	GSHP	Radiators															x				
41[illegible]	GSHP	Radiators															x				
443	ASHP	Radiators															x				
41[illegible]	GSHP	Radiators															x				
4[illegible]5	GSHP	Radiators															x				
44[illegible]	ASHP	Radiators																	x		
4[illegible]	GSHP	Radiators															x				
4[illegible]	GSHP	Radiators																			x
43[illegible]	GSHP	Underfloor																			x
44[illegible]	ASHP	Underfloor																			x
424	ASHP	Radiators																			x
43[illegible]	GSHP	Underfloor																			x
43[illegible]	GSHP	Underfloor																			x
Total			10	1	1	1	3	[illegible]	1	1	1	10	2	1	1	3	15	1	3	1	6

Table 3: Interventions by site and category

2. System Boundaries, Coefficient of Performance, Seasonal Performance Factor and System Efficiency

This section describes a range of different methods for determining seasonal performance of heat pumps and the differences between these methods.

In very broad terms, the efficiency of a heat pump may be defined as the ratio of heat output to the electricity used. This ratio is dependent on (amongst other things) the temperature of the source (air or ground), the flow temperature of the heat provided and the range of electricity inputs included in the system boundary.

This section describes the difference between various definitions of efficiency (coefficient of performance, seasonal coefficient of performance, seasonal performance factor and system efficiency) and also the range of different system boundaries that can be used (for example, some measures of efficiency include the auxiliary heating by the internal electric cassette).

It is important to distinguish between three difference concepts:

- ***Coefficient of performance***
- ***Seasonal coefficient of performance***
- ***Seasonal performance factor.***

The ***coefficient of performance (COP)*** is determined by laboratory testing at defined source and heat flow temperatures, for example, a 7°C ambient temperature and flow temperature of 45°C. The temperatures at which the COP is measured must always be quoted, otherwise the concept is meaningless.

The European standard for these tests is EN 14511 [7] (described in detail in section 2.2.1). Table 4 shows some published results for a typical air-source heat pump on the market [8]:

Ambient temperature(°C)	Central Heating flow temperature (°C)		
	35	45	55
-15		2.2	
-7		2.65	
2	3.84	3.28	
7	4.39	3.69	3.18

Table 4: Manufacturers' specified COP values at different ambient and central heating flow temperatures for a typical air-source heat pump

The ***seasonal coefficient of performance (SCOP)*** is a **modelled** estimate of the efficiency of a heat pump in a given climate. It is based on laboratory measurements of coefficient of performance, combined with the climate data for a given location. The relevant European standard is EN 14825 [9].

The ***seasonal performance factor (SPF)*** is the ***measured*** annual efficiency of a heat pump ***at a particular location***.

In each case, it is important to specify which electricity inputs and heat outputs are included in the calculation. This is the concept of ***system boundary***.

Section 2.1 presents the system boundaries as presented by the EU SEPEMO project, which defines rules for measuring annual seasonal performance factor.

Section 2.2 presents the system boundaries for EN 14511 [7] (which measures COP), EN 14825 [9] (which estimates SCOP), EN 15316-4-2 [10] (which estimates SCOP) and VDI 4560-1 [11] (which estimates SCOP).

Section 2.3 presents the system boundaries defined in the EU Renewable Energy Sources Directive [12] (which refers to a calculated seasonal performance factor, SPF) and the EU Eco-Design Directive [13].

Section 2.5 presents the system boundaries for monitoring in the Renewable Heat Premium Payment Scheme.

Sections 2.5 and 2.6 present the monitoring configurations for Phases I and II of the Energy Saving Trust field trials and how the system efficiency relates to the SEPEMO definitions [14].

Section 2.7 shows a summary table of the various definitions of system boundaries, the relative merits of which are discussed in section 2.8. Finally, section 2.9 discusses data checking procedures.

2.1. System Boundaries for Calculation of SEPEMO Seasonal Performance factors

In 2009, the SEPEMO-build project (**SE**asonal **PE**rformance factor and **MO**nitoring for heat pump systems in the building sector) was launched by the European Commission. One of the aims of this project was to develop clear, consistent methods for comparing performance of heat pumps.

The SEPEMO project examined both heating and cooling; here we are concerned with heating only. Four boundaries were defined for assessing seasonal performance of the heating circuit. These boundaries are denoted SPF_{H1-4} and are reported in [14].

Table 5 presents the designations of electricity inputs and heat outputs for the SEPEMO definitions of seasonal performance factors. Note that, for the purposes of this report, the single electrical backup heater has been replaced by an auxiliary space heater (E_{Aux}) and an immersion for domestic hot water $E_{Immersion}$ and the heat provided by the auxiliary heater and immersion have been separated into two quantities, Q_{H_aux} and Q_{W_aux}.

Quantity		Explanation
Heat	Q_{H_hp}	Space heating provided by the heat pump
	Q_{W_hp}	Water heating provided by the heat pump to the domestic hot water cylinder
	Q_{H_aux}	Space heating, provided by the auxiliary electric heater
	Q_{W_aux}	Water heating, provided by the electric immersion to the domestic hot water cylinder (=$E_{Immersion}$)
Electricity	$E_{S\_fan/pump}$	Electricity used by the source pump (for ground-source) or fan (for air-source)
	E_{HP}	Electricity used by the heat pump (excluding the ground loop/air inlet and auxiliary heating/immersion)
	$E_{Immersion}$	Electricity used to supplement domestic hot water production
	E_{Aux}	Electricity used to supplement space heating
	E_{bt_pump}	Electricity used by the buffer tank pump (if present)
	$E_{B\_fan/pump}$	Electricity used by the fan or pump of the central heating system

Table 5: Designations of electricity inputs and heat for SEPEMO definitions of seasonal performance factors

The four seasonal performance factors are illustrated in Figure 1, taken from [14].

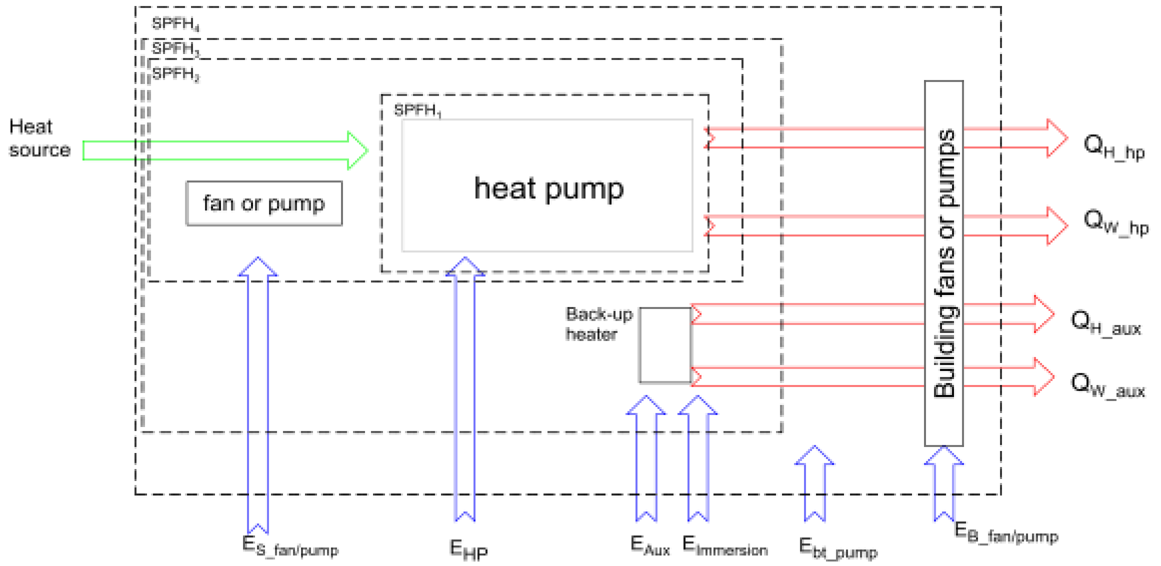


Figure 1: System boundaries for space and water heating circuits, as defined in the SEPEMO project

2.1.1. SPF_{H1}

SPF_{H1} evaluates the performance of the refrigeration cycle. The system boundaries are similar to the coefficient of performance COP defined in EN 14511 [7], except that EN14511 also includes a small part of the pump consumption to overcome head losses and most of the fan consumption. Figure 2 shows the system boundaries for SPF_{H1}.

$$SPF_{H1} = \frac{(Q_{H\_hp} + Q_{W\_hp})}{(E_{HP})} \qquad \text{[Equation 1]}$$

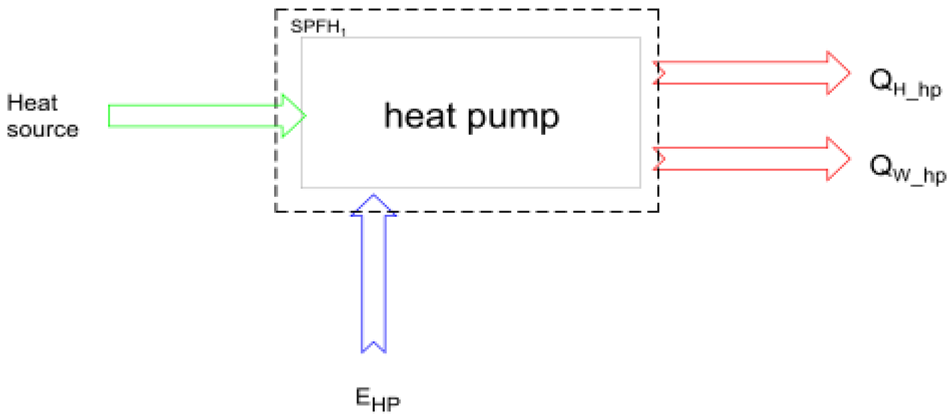


Figure 2: System boundary for SPF_{H1}, as defined in the SEPEMO project

2.1.2. SPF_{H2}

This system boundary consists of the heat pump unit and the equipment to make the source energy available for the heat pump, as shown in Figure 3. SPF_{H2} evaluates the performance of the heat pump operation. This boundary is similar to that used for determining $SCOP_{NET}$ in EN 14825 [9] and the EU Renewable Energy Sources Directive [12] requirements, see Table 6. For heat pumps with an integral electrical backup heater, consumption of this heater should be subtracted from the overall electrical supply to the heat pump.

$$SPF_{H2} = \frac{(Q_{H\_hp} + Q_{W\_hp})}{(E_{S\_fan/pump} + E_{HP})} \quad \text{[Equation 2]}$$

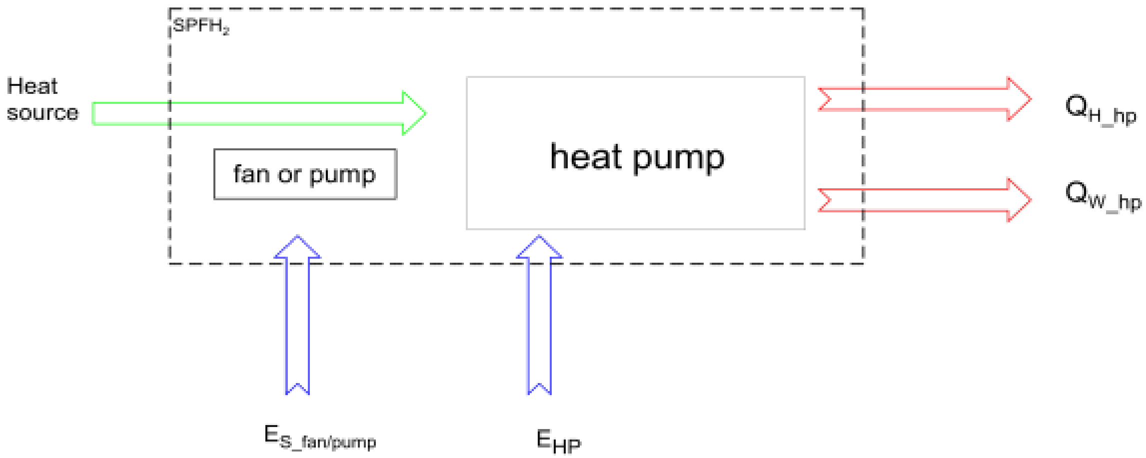


Figure 3: System boundary for SPF_{H2}, as defined in the SEPEMO project.

2.1.3. SPF_{H3}

This system boundary consists of the heat pump unit, the equipment to make the source energy available and the auxiliary heater (referred to as "backup" in the SEPEMO documentation), see Figure 4. SPF_{H3} represents the heat pump system and thereby it can be used for comparison to conventional heating systems (e.g. oil or gas).

It should be clear that this definition includes both backup for the central heating and the domestic hot water immersion (in European houses, with basements, the domestic hot water tank is often integral to the heat pump and so a single electrical cassette can supply both auxiliary space heating and water heating; in the UK, space requirements mean that the domestic hot water tank is often separate from the heat pump and therefore has a separate immersion). For this reason, the SEPEMO drawing has been amended to show the electricity for auxiliary heating and immersion separately.

This system boundary is similar to that for the SPF in VDI 4650-1 [11], EN 15316-4-2 [10] and the $SCOP_{ON}$ in EN 14825 [9]. For *monovalent* heat pump systems (i.e. heat pump systems with no electrical backup, either for space or water heating) SPF_{H3} and SPF_{H2} are identical.

$$SPF_{H3} = \frac{(Q_{H\_hp} + Q_{W\_hp} + Q_{H\_aux} + Q_{W\_aux})}{(E_{S\_fan/pump} + E_{HP} + E_{Aux} + E_{Immersion})} \qquad \text{[Equation 3]}$$

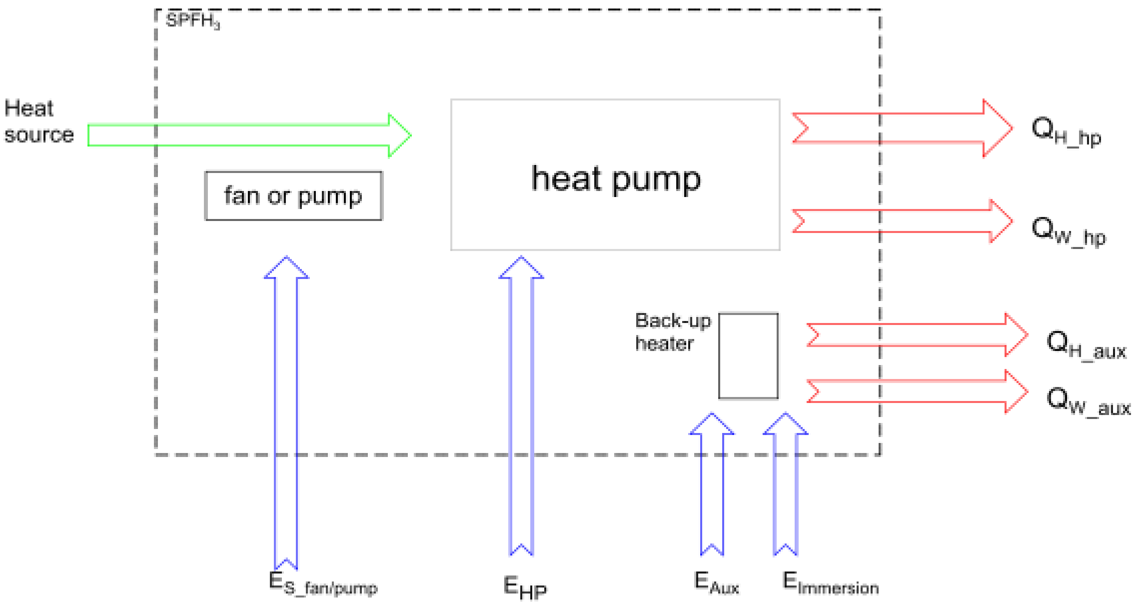


Figure 4: System boundary for SPF_{H3}, as defined in the SEPEMO project

Note $E_{Immersion}$ and E_{Aux} are shown separately instead of a single electrical backup, E_{bu} and Q_{H_aux} and Q_{W_aux} shown separately, instead of a single quantity for backup heat Q_{HW_bu} as per SEPEMO.

2.1.4. SPF_{H4}

SPF_{H4} consists of the heat pump unit, the pumps or fans to make the source energy available, the auxiliary electric heater and domestic hot water immersion and all auxiliary pumps including those on the heat sink system (eg central heating circuit pumps and buffer tank pumps). See Figure 5.

$$SPF_{H4} = \frac{(Q_{H\_hp} + Q_{W\_hp} + Q_{H\_aux} + Q_{W\_aux})}{(E_{S\_fan/pump} + E_{HP} + E_{Aux} + E_{Immersion} + E_{bt\_pump} + E_{B\_fan/pump})} \quad \text{[Equation 4]}$$

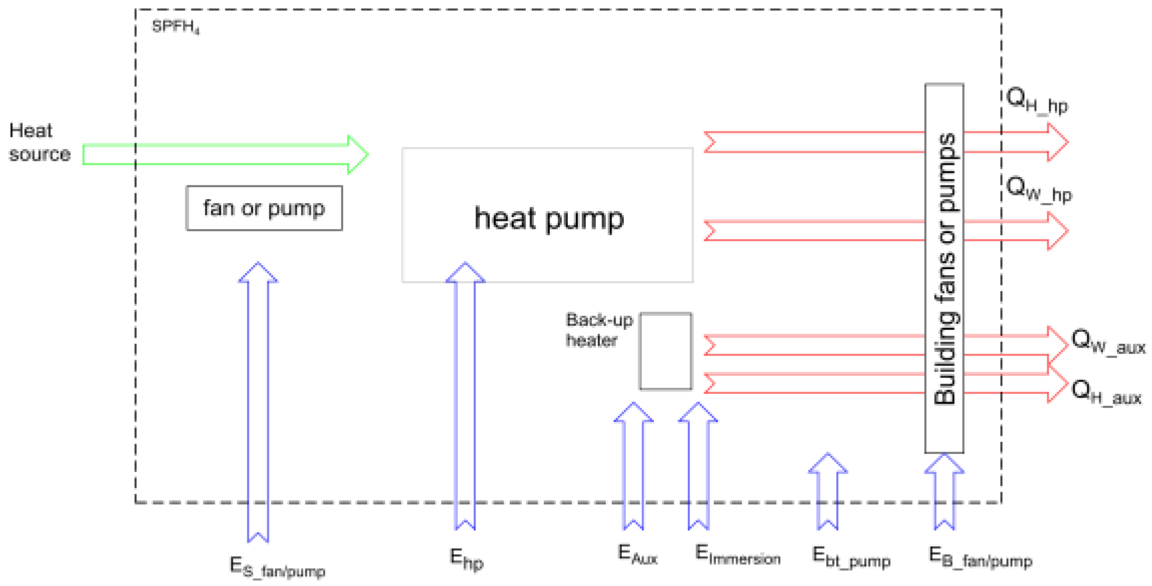


Figure 5: System boundary for SPF_{H4}, as defined in the SEPEMO project

Note E_{aux} and $E_{Immersion}$ are shown separately, instead of a single electrical backup, E_{bu} and Q_{H_aux} and Q_{W_aux} shown separately, instead of a single quantity for backup heat Q_{HW_bu} as per SEPEMO.

2.1.5. Consideration of defrost

In conditions of low temperature (0°C to 5°C), air-source heat pumps can be affected by the build-up of frost on the outdoor heat exchanger. This reduces performance and, for this reason, air-source heat pumps employ a defrost cycle. Ground-source heat pumps are not affected by defrost.

Defrosting can be achieved by three methods;

- Hot gas defrosting
- By direct use of electric energy
- By reverse flow

In the first case, "hot gas defrosting"[1], the capacity of the heat pump is reduced and so the heat supplied to the central heating and domestic hot water cylinder is reduced for the same level of electrical input.

In the case of direct electric heating, an additional term, $E_{defrost}$ is added to the denominator in all calculations of SPF (i.e. SPF_{H1-4}).

In the case of reversed heat flow, a term $Q_{defrost}$ is subtracted from Q_{H_hp} in the numerator for all calculations of SPF.

The most commonly used method in the Energy Saving Trust field trial was by reverse flow.

2.2. System Boundaries for EN 14511, EN 14825 EN 15316-4-2 & VDI 4650-1

2.2.1. EN 14511

EN 14511 [7] describes the testing procedure to calculate the ***coefficient of performance (COP)*** or energy efficiency ratio (EER). Tests are carried out to a range of specified ambient and heat flow temperatures.

The average electrical power input of the unit within the defined interval of time is obtained from:

- the power input for operation of the compressor and any power input for defrosting;
- the power input for all control and safety devices of the unit and;
- the proportional power input of the conveying devices (e.g. fans, pumps) ***for ensuring the transport of the heat transfer media inside the unit.***

Thus the system boundary is different to all of the SEPEMO boundaries for seasonal performance factor. It is similar to that for system boundary of SPF_{H1}, with the difference being that EN 14511 takes account of a small part of the pump consumption on the source side to overcome head losses and a proportion of fan/pump consumption on the sink side to overcome head losses.

[1] In "hot gas defrosting", a proportion of the superheated refrigerant is diverted from the compressor through a heat-exchanger to melt accumulated ice, whereupon the heat transfer fluid condenses and returns to the refrigeration circuit. The net effect is that the capacity of the heat pump reduces.

Defrost is accounted for in the same way as for SPF, i.e. as described in section 2.1.5.

2.2.2. EN 14825

EN 14825 [9] is concerned with the modelling of ***seasonal coefficient of performance (SCOP)***, defined according to 3 climate zones and for a range of space heating emitter temperatures. It is based on measurements of COP according to EN 14511.

For heating only systems, EN 14825 defines two quantities: the ***net seasonal coefficient of performance, $SCOP_{NET}$***, and the ***seasonal coefficient of performance in "ON" mode $SCOP_{ON}$***.

$SCOP_{NET}$ has boundaries similar to those for SPF_{H2}, although it only includes a proportion of the pump consumption on the source side to overcome head losses and a proportion of fan/pump consumption on the sink side to overcome head losses.

$SCOP_{ON}$ has boundaries similar to those for SPF_{H3}, although it only includes a proportion of the pump consumption on the source side to overcome head losses and a proportion of fan/pump consumption on the sink side to overcome head losses. It includes the electricity used by supplementary heaters for space and water heating.

Defrost is accounted for in the same way as for SPF, i.e. as described in section 2.1.5.

2.2.3. EN 15316-4-2

EN 15316-4-2 [10] describes a bin method for the calculation of seasonal system efficiency, based on the heating load evolution, heating curve of the heat pump, climate conditions and standard heat pump testing points. This system boundary contains the heat pump unit, the pumps/fans to make the source energy available as well as internal and external boilers and back-up heaters. This equates to boundary SPF_{H3}. The difference is that in EN 15316-4-2 the thermal losses of the heating system are calculated.

Defrost is accounted for in the same way as for the SEPEMO SPF's, i.e. as described in section 2.1.5.

2.2.4. VDI 4650-1

VDI 4650-1 [11] is used for measuring seasonal performance factor, SPF. The SPF calculation according to this regulation includes the heat source pumps, the auxiliary space and water heaters and the auxiliary drive energy for space heating (for pressure losses of the condenser) as mentioned in the EN 14511.

The system boundaries are similar to those for SPF_{H3}, but only a proportion of the energy used by central heating pumps and domestic hot water pumps is included.

Defrost is accounted for in the same way as for the SEPEMO SPF's, i.e. as described in section 2.1.5.

2.3. The EU Renewable Energy Sources Directive and EU Ecodesign Directive

2.3.1. EU Renewable Energy Sources Directive

The Renewable Energy Sources Directive [12] defines the sources of heat that are considered as renewable in the EU. The aim of the directive is to increase the proportion of renewable energy (both heat and power) generated in the EU. Member states must report annually on the amount of renewable heat generated in each country to comply with the directive.

Under this directive, heat pumps are considered renewable sources, provided that the SPF >1.15* 1/η, where η is the average ratio of the efficiency of the EU electricity grid. **Using figures for the average efficiency of electrical generation in the EU in 2010 [15], this equates to a requirement that the SPF for electrically driven heat pumps is greater than 2.5.**

It should be noted that the SPF referred to in the directive is a calculated figure, based on laboratory measurements and locality-specific climate data, rather than a measured, in-situ figure. The European Commission recently published the methodology for calculating SPF to be used to demonstrate compliance with the EU Renewable Energy Sources Directive [16]. This document states that the appropriate system boundary for assessing compliance is SPF_{H2}, i.e. it includes the electricity supplied to the compressor and refrigeration circuits and electricity for the inlet fan or ground source pump.

Finally, it should be remembered that increasing the SPF above 2.5 increases the amount of renewable heat generated.

2.3.2. EU Eco-design Directive

The EU Eco-design Directive [13] aims to exclude environmentally damaging products from the market; this covers many issues, one of which is energy efficiency. Thus the focus is different to that of the EU Renewable Energy Sources Directive [12], which is aimed at increasing the generation of renewable energy.

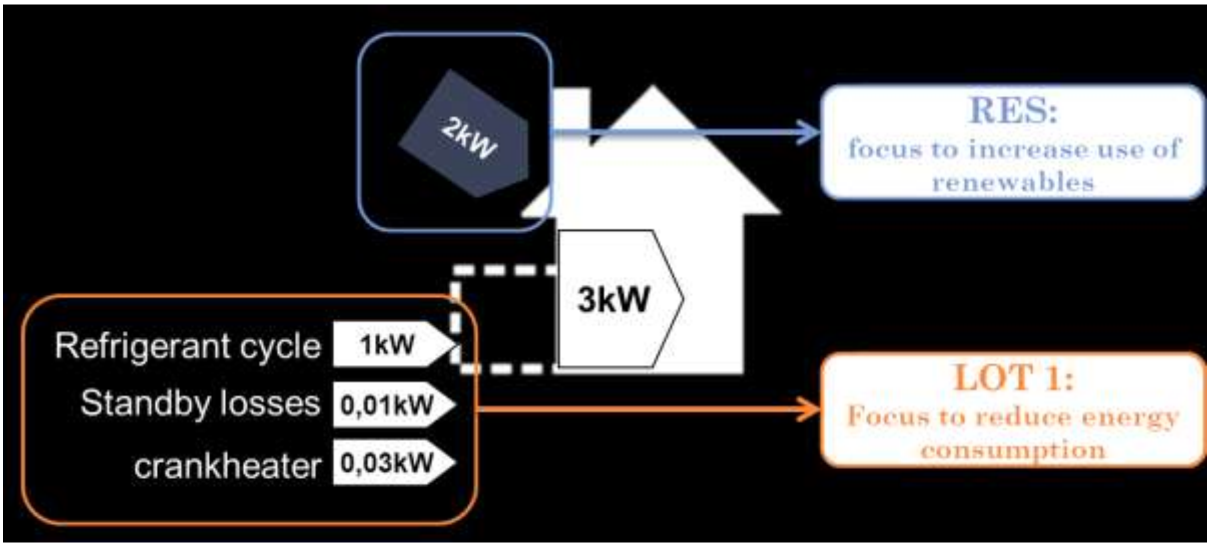


Figure 6: Schematic to demonstrate the focus of the EU Eco-design Directive and that of the EU Renewable Sources Directive, as applied to heat pumps

The space heating element of heat pumps is included in Lot I of the Eco-design Directive (boilers) while the water heating element is included in Lot II (water heaters). Cooling is included in Lot 10, but this is of little relevance to the UK domestic sector and so will not be considered in the remainder of this report.

Lot I of the Eco-design Directive specifies a methodology for calculating the primary energy required to produce a given level of output space heating (η_s). Lot II describes the test procedures used to establish the efficiency of water heating.

The European Heat Pump Association and others provide a clear comparison of the application of the EU Renewable Energy Directive and the EU Eco-design directive (Lot I) to heat pumps, see Table 6, reproduced from reference [17].

Both directives specify calculation methods for seasonal coefficients of performance, but the methodologies are not the same; in particular, the Eco-design Directive takes account of additional backup heaters and due to the auxiliary modes (active modes, standby modes, off modes, crank heater modes, thermostat off modes, as well as pump power effects and degradation due to on/off cycling).

Electrical parameter included	Eco-design Directive Lot I Space heating efficiency, ηs	Renewable Energy Sources Directive SPF
Active mode	YES	YES
Additional backup heaters	YES	NO
On/off cycling	YES	YES
Thermostat off	YES	NO
Standby	YES	NO
Off mode	YES	NO
Crankcase heater	YES	NO
Ground source pump power	YES	YES
Effect of controls	YES	NO

Table 6: Comparison of electricity inputs for the assessment of space heating efficiency in the Eco-Design Directive (Lot I) and the seasonal performance factor from the Renewable Energy Sources Directive (from [17])[2]

2.4. Monitoring for the Renewable Heat Premium Payment Scheme

The Renewable Heat Premium Payment scheme is a DECC policy, designed to assist householders to install renewable heat generating measures such as heat pumps and biomass boilers in their homes. The scheme was divided into three parts; social housing, private houses and community schemes.

A selection of heat pumps installed under the Renewable Heat Premium Payment Scheme have been monitored, with the aim of estimatingSPF_{H1}-SPF_{H4} for each site. Analysis is currently in progress and will be completed in Spring 2014.

2.5. System Efficiency as specified in Phase I of the Energy Saving Trust Field Trials

In Phase I, the specification was designed to be compatible with Energy Saving Trust's condensing boiler field trials, and therefore **required measurement of the heat of the domestic hot water actually used**, rather than measurement of the heat supplied to the hot water cylinder. The protocol was agreed by the funding board and approved by the peer review committee. Figure 7 presents the monitoring schematic.

[2] The table from reference [17] also includes a line marked "water pump", which it says is included in both the Eco-design directive and the RES SPF. It is not clear what this refers to; it does not refer to the circulation pump on the central heating side.

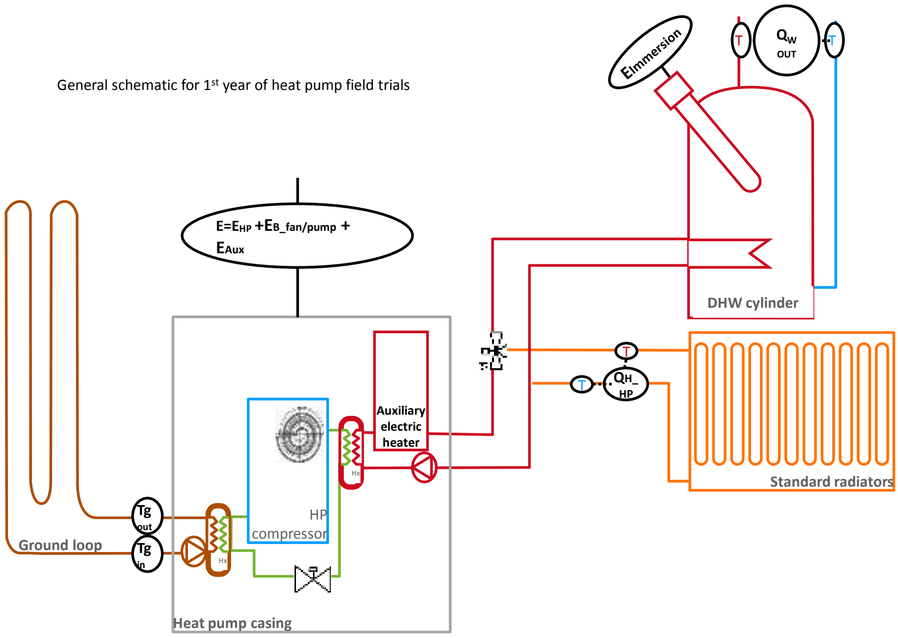


Figure 7: Schematic of monitoring protocol for Phase I of the Energy Saving Trust heat pump field trials

Thus, the focus of the study was the "system efficiency" (SEFF), rather than the efficiency of the heat pump only. The definition of system efficiency is given below:

$$SEFF = \frac{(Q_{H\_hp} + Q_{H\_aux} + Q_{W_{OUT}})}{(E_{S\_fan/pump} + E_{hp} + E_{Aux} + E_{Immersion} + E_{bt_{pump}} + E_{B\_fan/pump})}$$

Where:

Q_{W_OUT} = heat of domestic hot water **used** by the householder (as opposed to heat supplied to the hot water cylinder)

2.6. System Efficiency as specified in Phase II of the Energy Saving Trust Field Trials

The objective of Phase I was to determine the efficiency of the entire heating system, denoted as 'system efficiency'.

In Phase II, the technical monitoring specification was as in Phase I, with the addition of a heat meter to monitor heat output from the heat pump itself. This enables calculation of the seasonal performance of the heat pump itself (as described in the section on SEPEMO seasonal performance factors).

Where appropriate, additional electricity meters were also installed, for example, to monitor the electricity used by the heat pump compressor only or to measure the consumption of the pumps on the central heating side. Figure 8 shows the schematic.

The resulting configurations allow direct calculation of SPF_{H4} in all cases. In some cases, SPF_{H3} and SPF_{H2} can be deduced directly from the measured data. In all remaining cases, estimates can be made of $SPF_{H1\text{-}H3}$ by examining scatterplots and time-series plots to identify use of the auxiliary electric heat supplied and by making estimates of the consumption of circulation pumps / fans.

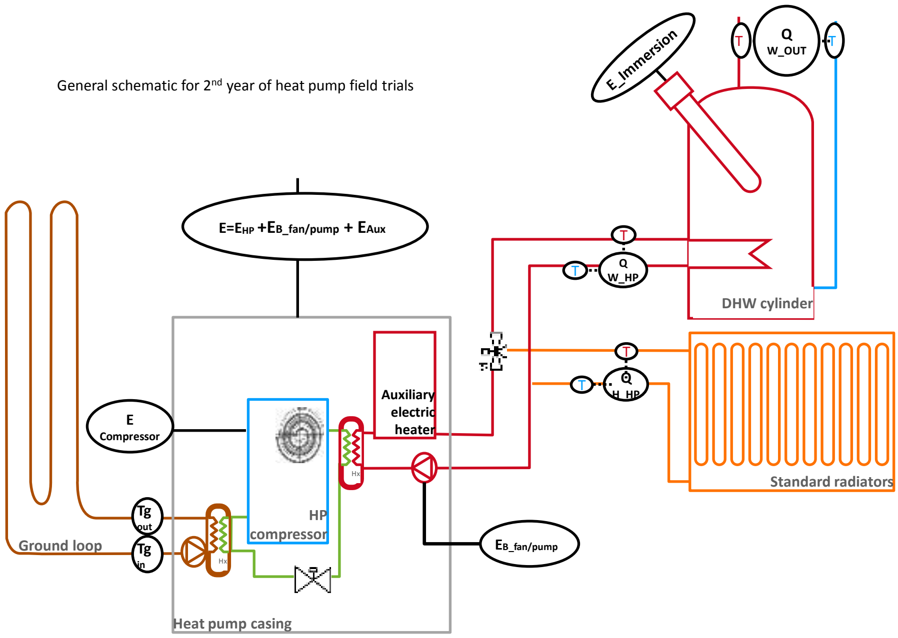


Figure 8: Schematic of monitoring protocol for Phase II of the Energy Saving Trust heat pump field trials

2.7. Summary of parameters included for different system boundaries

Table 7 summarises the components taken into account in the various system boundaries for SEPEMO, various EU standards and the "system efficiency" used in the Energy Saving Trust Heat Pump Field Trials.

	Component	SPF_{H1}	SPF_{H2}	SPF_{H3}	SPF_{H4}	EN 14511	EN 14825 $SCOP_{NET}$	EN 14825 $SCOP_{ON}$	VDI 4650-1	EN15316 4-8	EU RES Directive	System efficiency EST trials
Heat *	Heat supplied by heat pump	x	x	x	x	x	x	x	x	x	x	
	Heat supplied to central heating circuit											x
	Heat supplied to domestic hot water cylinder											
	Heat extracted from domestic hot water cylinder											x
Electrical components	Compressor	x	x	x	x	x	x	x	x	x	x	x
	Heat source fan/ pump	---	x	x	x	head losses	head losses	head losses	x	x	x	x
	Back-up for both space heating and domestic hot water	---	---	x	x	---	--	x	x	x		x
	Buffer tank pump	---	---	---	x	---	---	---	---	x		x
	Space heating and domestic hot water fans/pumps	---	---	---	x	head losses	head losses	head losses	head losses	x		x

Table 7: Summary of parameters included in different system boundaries

*Note that the heat supplied by the heat pump is the sum of the heat supplied to the central heating circuit and the heat supplied to the domestic hot water cylinder, unless there is a buffer tank.

2.8. Discussion

As demonstrated in the previous section, there are many different ways to define system boundaries. For the purposes of the consumer, the most important system boundary is the one we have called "system efficiency", as it gives an indication of the overall cost of providing the heat that is actually used by the householder. However, the system efficiency is very much affected by the householders' domestic hot water consumption. System efficiency was the parameter selected for analysis in Phase I and therefore, comparisons of results from the two phases of the trial are made on this basis.

For Phase II, it has generally been possible to estimate a range of system performance factors for each site. Comparison of these different factors yields insights into the quality of the installation and operational parameters.

DECC considers that the most appropriate system boundary to consider when designing a heat pump system is SPF_{H4}; this takes into account all auxiliary electricity consumption for immersion or space heating and the consumption of circulation pumps. The MCS 022 Heat Emitter Guide [18] is based on SPF_{H4} (for space heating only).

3. Analysis

This section presents histograms of system efficiency and space and water heating efficiencies.

The starting point for all analysis is the quality controlled 5-minute data of heat flows, electricity consumption and a range of temperatures (ambient, indoor, flow and return to ground, flow and return from central heating and hot water cylinder temperatures).

The analysis reported in this document has been carried out the Energy Saving Trust's contractors, Kiwa Gastec at CRE and EA Technology and by DECC. Details of the instrumentation and data checking are presented in Appendices A & B, while the methodology for calculating the various seasonal performance factors is described in Appendix C. Appendix D describes the procedure for temperature correction.

Section 3.1 presents the comparison of temperature-corrected system efficiencies from Phase I with those from Phase II. Section 3.2 presents the various components of electricity consumption for auxiliary heating, immersion, pumps and fans and section 3.3 presents histograms of SPF_{H2}, SPF_{H4} and system efficiency for both air and ground-source heat pumps. Finally, section 3.4 presents space and water heating efficiencies, where it has been possible to separate the two. These are SPF_{H2}.

Sections 4-8 present a range of case studies, showing the effect of specific interventions.

Section 8 summarises the results.

Section 9 presents recommendations.

3.1. Comparison of System Efficiencies from Phases I and II

As discussed in section 2.5, the efficiency calculated for Phase I was the system efficiency. System efficiency is influenced by two main factors:

- Ambient temperature
- Amount of domestic hot water used and temperature to which this water is heated.

  In order to compare system efficiencies from Phases I and II, the data have corrected for the effect of ambient temperature. See Section 14 (Appendix D) further details of the procedure.

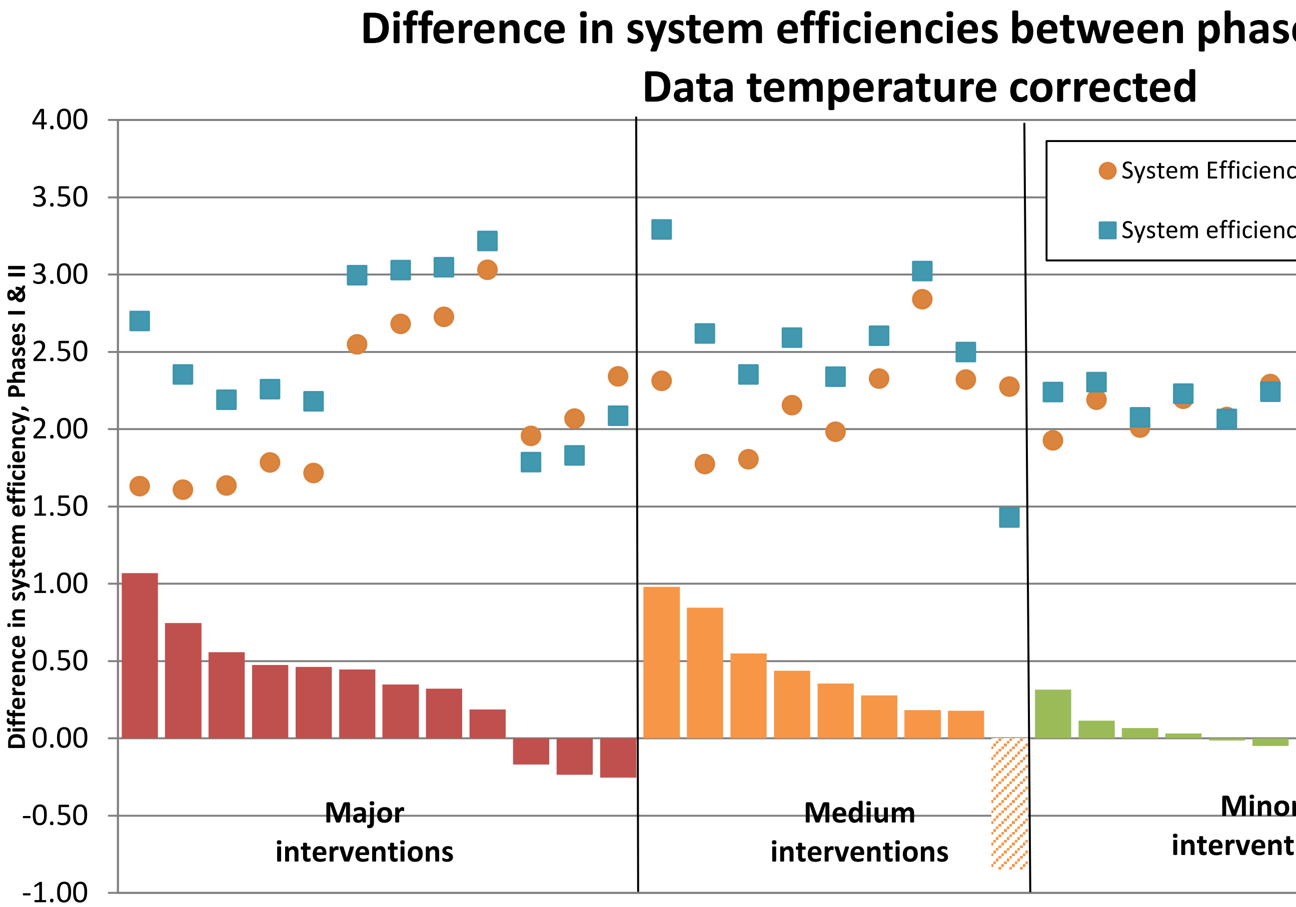


Figure 9 presents the difference in temperature-corrected system efficiency between Phases I and II. The orange points show the Phase I system efficiency, while the blue ones show the system efficiency for Phase II.

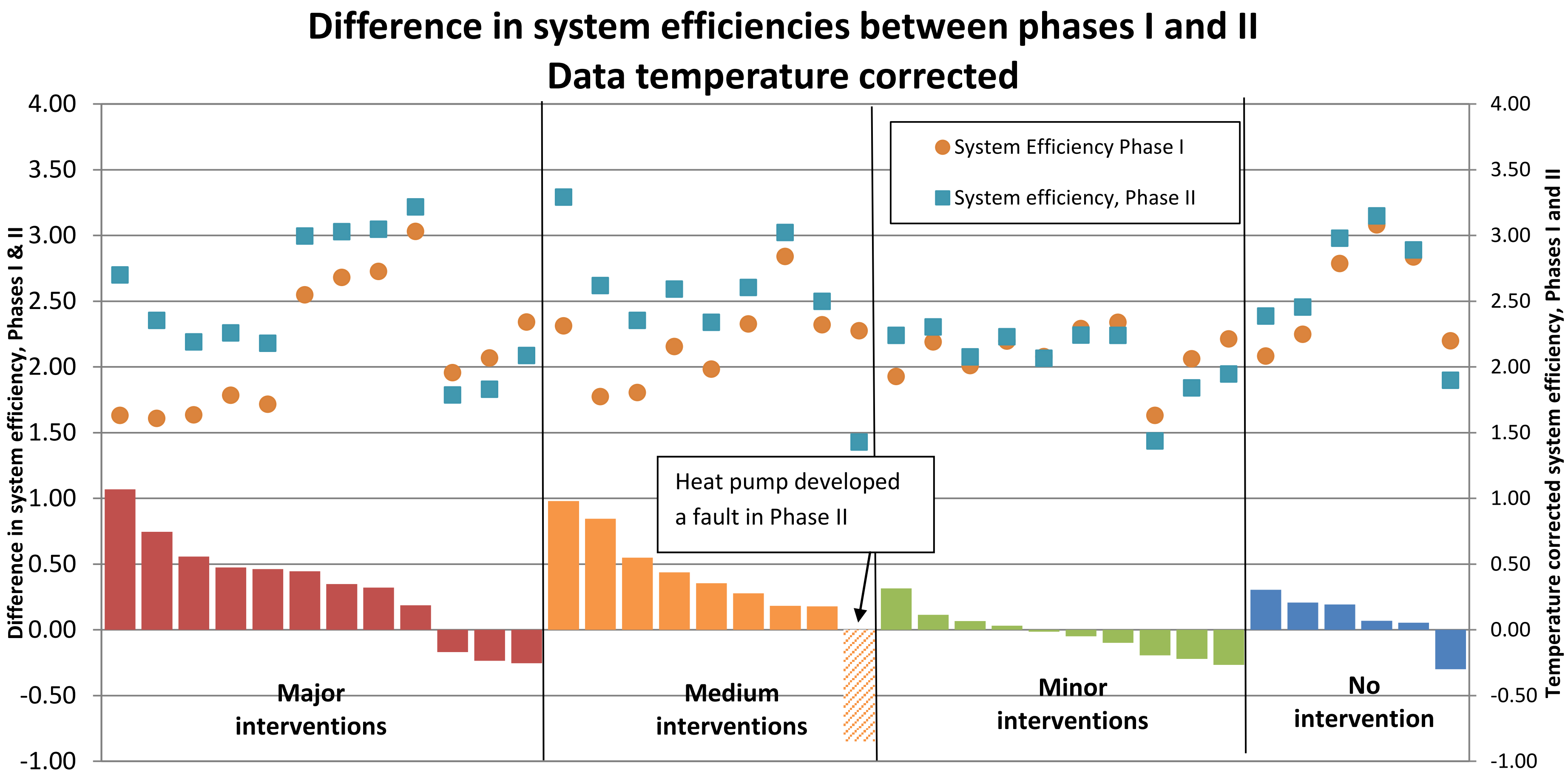


Figure 9: Change in temperature-corrected system efficiency from Phase I to Phase II (37 sites, one site with faulty heat meter in Phase I removed from minor intervention category)

3.1.1. Major Interventions

Major interventions have been successful in increasing the system efficiency. System efficiency improved at nine of the 12 sites (by more than 0.5 for three sites and by between ~0.2 and ~0.47 for a further five sites). Three sites showed reduced performance (by between 0.17 and 0.25).

The most improved site was site 418, where the temperature corrected system efficiency increased from 1.63 to 2.70. This was a complex site, where the domestic hot water was heated by an exhaust air-source heat pump while the space heating was provided by an air-source heat pump. During Phase I, the immersion in the exhaust air-source heat pump was used excessively. Both heat pumps were replaced in phase II and the immersion in the exhaust heat pump was switched off. Circulation pumps were replaced with low energy dc pumps.

In nine cases, the major intervention was the replacement of a heat pump, sized according to the manufacturers' procedures at the time, i.e. not necessarily compliant with MCS MIS 3005 Issue 3.1. In one case, the central heating circuit was modified so that the area heated by the heat pump was reduced; this is equivalent to increasing the size of the heat pump. The final "major" intervention consisted of moving the heat pump, which was previously located at the end of the garden closer to the house, thereby reducing the very considerable heat losses from the pipes. It is important to note that some heat pumps were replaced with smaller heat pumps as shown in Table 8 below.

	Heat pump capacity		
	Decreased	Same	Increased
Number of heat pumps	5	4	3 (includes one example of heat pump heating smaller area)

Table 8: Change in capacity of heat pumps for sites with major interventions

For two of the three sites for which system efficiency was reduced in Phase II, the reason was increased immersion consumption for domestic hot water. This is discussed in the case studies, see sections 5-7.

3.1.2. Medium Interventions

Eight out of nine systems showed improved performance, with system performance improving by more than 0.3 in five cases. The greatest improvement, from 2.31 to 3.29, was at a site where software was altered to reduce the use of the auxiliary heater.

One heat pump system showed a large reduction in system efficiency; this was due to a fault from 14/12/2011-21/02/2012, during which time the system was using the internal auxiliary electric heating.

In all but one case, variable speed DC pumps were fitted. The effectiveness of these can be seen by comparing SPF_{H3} and SPF_{H4} for the sites. Figure 10 demonstrates that the systems with variable speed DC pumps had, on average, a lower difference between SPF_{H3} and SPF_{H4} (0.06 as opposed to 0.13).

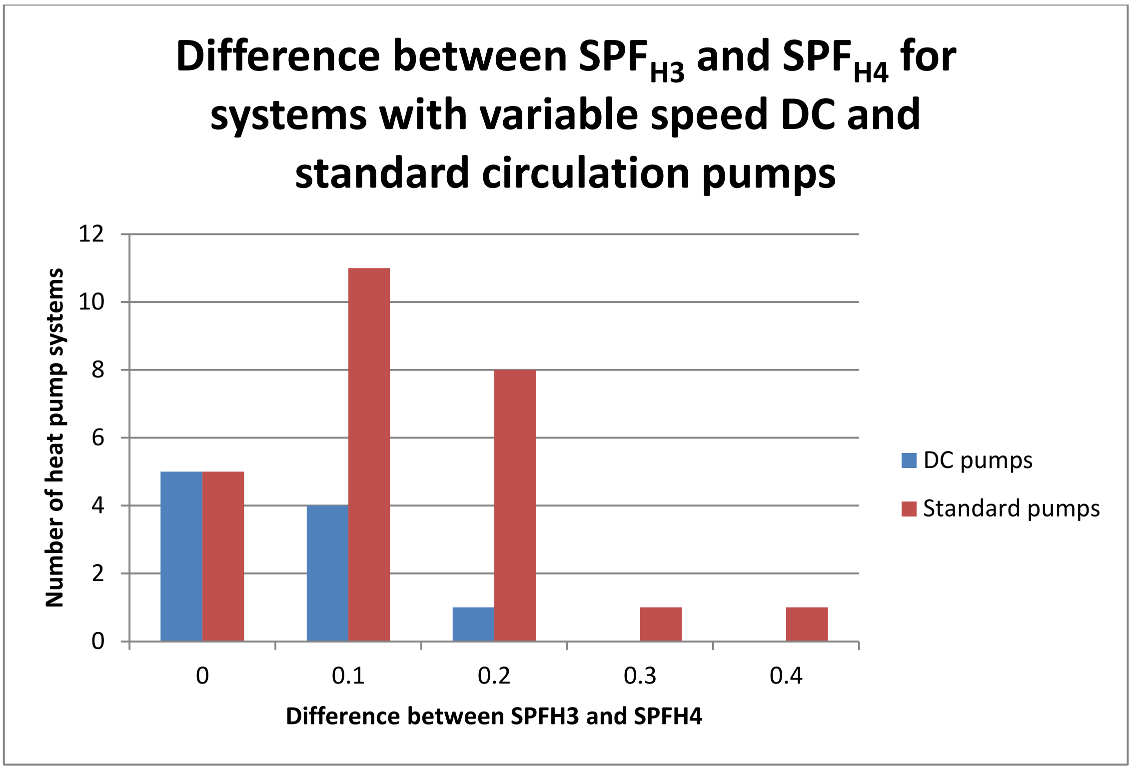


Figure 10: Difference between SPF_{H3} and SPF_{H4} for systems with variable speed DC and standard circulation pumps

3.1.3. Minor Interventions

11 sites were selected for minor interventions. In one case, the heat meter data from Phase I was re-examined and found to be faulty. For this reason, the site has been omitted from this analysis.

Only one showed a significant improvement in system efficiency (0.3), while, for six of the sites, the magnitude of the difference in system efficiency was less than 0.1. The remaining three sites showed a decrease in performance of around 0.2.

Closer examination of these sites indicated that, for two of these three sites, the proportion of domestic hot water used in the second phase had increased significantly, thereby decreasing the perceived overall system efficiency, which is a weighted average of the efficiencies of space and water heating (see Table 9). Furthermore, for site 440, the overall amount of energy used for space and water heating dropped from 6911 in Phase I to 2305 kWh in Phase II.

Site		Phase I	Phase II
440	Space heating kWh	4779	1230

	Water heating[3] kWh	2132	1075
	Proportion of water heating	31%	47%
	Temperature-corrected system efficiency	1.63	1.44
462	Space heating kWh	3408	3242
	Water heating[4] kWh	208	3046
	Proportion of water heating	6%	48%
	Temperature-corrected system efficiency	2.21	1.95
465	Space heating kWh	5228	5823
	Water heating[5] kWh	307	200
	Proportion of water heating	Near zero	Near zero
	Temperature-corrected system efficiency	2.06	1.84

Table 9: Proportion of space and water heating for sites 440, 462 & 465

The reasons for the reduction in performance at site 465 are not known. The overall heat delivered is roughly constant (5228 kWh in Phase I and 5823 kWh in Phase II) and the immersion was not used in either phase of the trial.

3.1.4. No Interventions

Out of the six sites that received no interventions, the temperature corrected system efficiencies increased significantly for three (>~0.2). For two sites, the change was negligible and for the final site, a decrease of 0.3 was registered.

3.2. Electricity consumption of different components

The heat pumps examined cover a range of configurations; central heating only, integral domestic hot water tanks (i.e. the tank is located within the heat pump box), separate domestic hot water tanks and systems with and without integral electric cassettes.

Electricity is used by a number of different components in the system:

- Circulation pumps for ground loop (ground-source heat pumps) or fans (air source heat pumps)
- Compressor
- Auxiliary space heater

[3] In this case, this means the heat in the water actually used by the householder, not the heat supplied to the tank
[4] As for note 2.
[5] As for note 2.

- Domestic hot water immersion
- Circulation pumps for central heating

Where possible, the electricity used by each component has been monitored separately. **The aim of this section is to present the electricity used by the auxiliary heater and domestic hot water immersion, as these quantities effectively represent the amount of necessary heat that the heat pump is unable to provide.**

In many cases, it was not possible to monitor the electric cassette separately; any heat used by the electric cassette was included in the electric demand of the heat pump. However, use of the auxiliary heater in these cases can usually be determined from inspection of the scatterplots of heat versus electricity demand.

Similarly, the electrical consumption of the ground loop (or air inlet fans) and the circulation pumps on the central heating side can generally be estimated from inspection of the time series of electricity demand by the heat pump, if metered data are not available.

Overall, 46 sites were available for analysis. Figure 11 shows that, on average, the compressor accounted for 82% of the electricity demand, with ground loop pumps or air inlet fans accounting for 6%, supplementary space or water heating accounting for 7% and circulation pumps accounting for 5%.

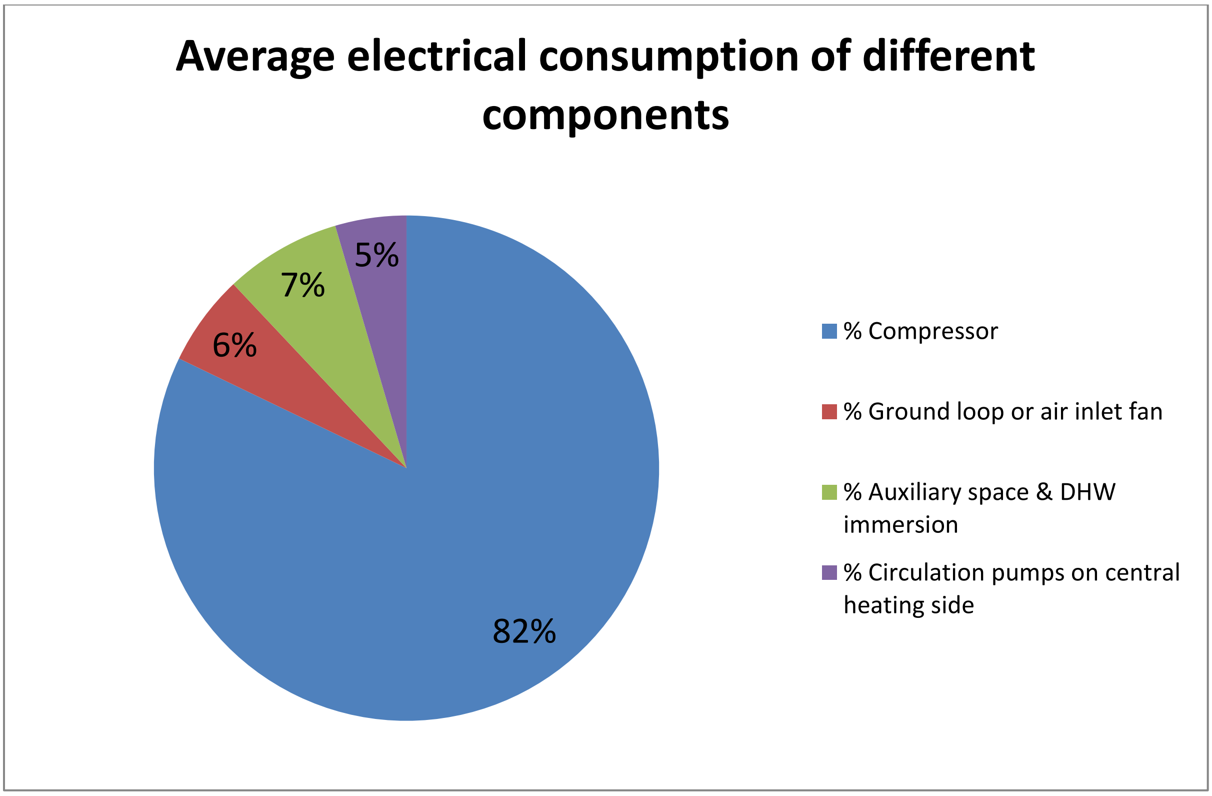


Figure 11: Average electrical consumption of different components of heat pumps in the trial

There were a number of sites with unusually high consumption of one or more components. In one case, the ground loop accounted for 26% of the electricity consumption, suggesting a fault or leak, while in one other the domestic hot water immersion accounted for 63%. There were also two cases of very high consumption by central heating circulation pumps (23% and 26% of total electrical demand respectively).

These examples illustrate how simple, electric monitoring of components could be used for fault diagnostics.

It should be noted that the EU Eco-design directive limits the energy consumption of glandless circulation pumps for heating and air-conditioning as of January 2013. Further tightening of these regulations will require that circulation pumps integrated in heat pumps and boilers are energy efficient as of 2015.

3.3. Analysis of defrost for air-source heat pumps

Figure 12 presents the heat used for defrosting air-source heat pumps as a function of the overall heat delivered during Phase II of the trial. The data are not temperature corrected; however, the three heat pumps with the greatest use of defrost are not located in the coldest parts of the country (one is in Belfast, one in Cheshire and one in Oxfordshire). More analysis is carried out on a site by site basis (see section 4.1.4).

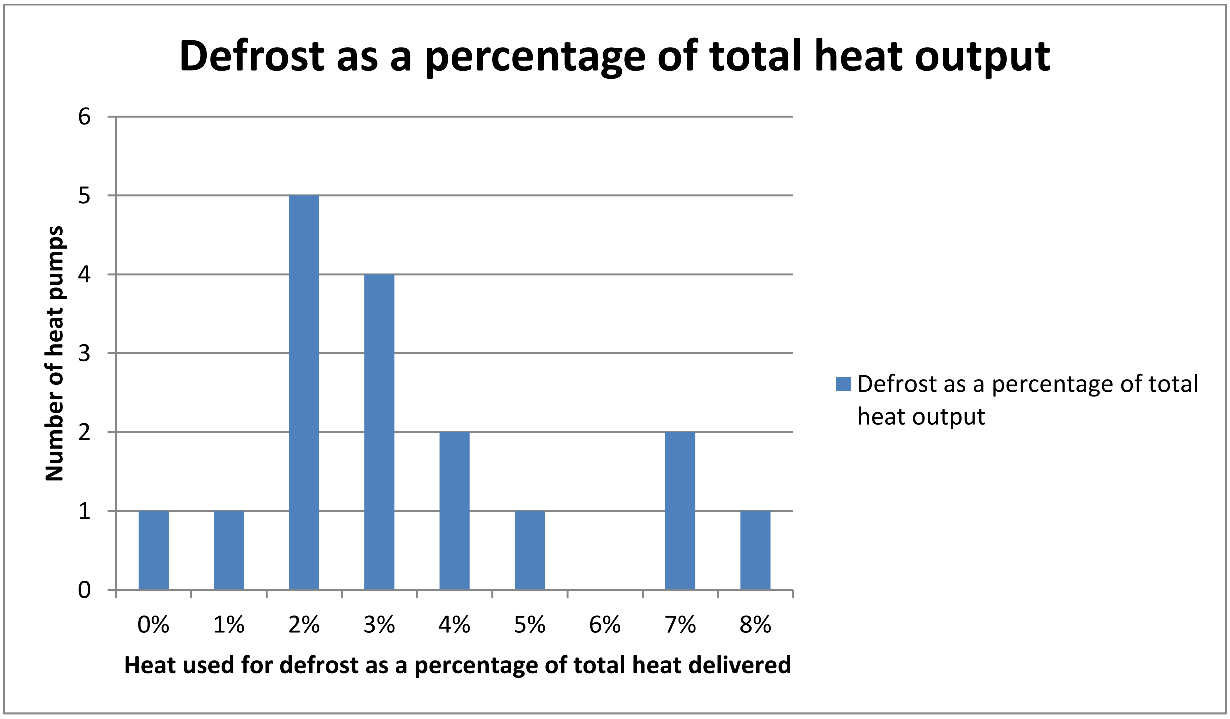


Figure 12: Defrost as a percentage of total heat output for the air-source heat pumps in the field trial

3.4. Histograms of performance for air- and ground-source heat pumps

This section presents histograms of performance for both air and ground-source heat pumps. The data refer to Phase II only and have not been temperature corrected.

Table 10 and

Figure 13 present SPF_{H2}, SPF_{H4} and system efficiency for the heat pumps in the trial. Note that it was not possible to calculate all of these quantities in every case because of metering arrangements or heat meter faults. For example, SPF_{H2} can only be calculated for 36 of the 44 systems examined in the trial.

The data has not been separated by emitter type or presence or absence of domestic hot water cylinders although, as noted in Table 1, the most common configuration in the sample for both ground and air-source heat pumps is supplying radiators and domestic hot water. On this basis, the ground-source heat pumps in the trial had significantly better SPF_{H2} and SPF_{H4} than the air-source heat pumps, although the small sample sizes should be noted.

		SPFH2	SPFH4	System efficiency	Proportion of systems considered renewable
Air-source	Average	2.72	2.45	2.16	9/15 – note that 5 out of the 9 heat pumps considered renewable were completely new installations and were MCS 3005 compliant.
	Standard deviation	*0.45*	*0.44*	*0.44*	
	Range	*2.2-3.9*	*2.0-3.7*	*1.7-2.7*[6]	
	Number of systems	*15*	*15*	*16*	
Ground-source	Average	3.08	2.82[7]	2.54[7]	20/21
	Standard deviation	*0.40*	*0.42*	*0.47*	
	Range	*2.2-3.9*	*2.0-3.9*[7]	*1.5-3.3*	
	Number of systems	*21*	*21*	*26*[7]	

Table 10: SPF_{H2}, SPF_{H4} and system efficiencies for Phase II (not temperature-corrected)

The European Commission states that the minimum level of SCOP for a heat pump to be considered renewable is 2.5 [27] [8]. The same document indicates that the system boundaries for this calculation are those of SPF_{H2}. From the top chart in

[6] One air-source heat pump had a particularly low system efficiency, partly due to relatively high domestic hot water use (around 90%) and due to long pipes and high heat losses from the tank. This point has been omitted from the system efficiency range.

[7] One ground-source heat pump developed a fault and had high auxiliary electricity use. This is shown as a shaded point in the middle and bottom charts of Figure 13, but is excluded from the SPF_{H4} and system efficiency columns of Table 10. SPF_{H2} is not affected by use of the auxiliary electricity and so results from this heat pump are included in the SPF_{H2} column of Table 10.

[8] "EU Commission decision of 1.3.2013 on establishing the guidelines for Member States on calculating renewable energy from heat pumps from different heat pump technologies pursuant to Article 5 of Directive 2009/28/EC", article 3.3

Figure 13, we can see that 9 of the 15 air-source heat pumps and 20 of the 21 ground-source heat pumps would be considered renewable under this definition. It is important to note that five out of the nine air-source heat pumps in this sample that meet the EU Renewable Energy Directive criterion were new installations, compliant with MCS MIS 3005 Issue 3.1.

There is a significant difference between SPF_{H2} (as used in the EU Renewable Energy Directive) and SPF_{H4}, SPF_{H2} being on average 0.3 higher than SPF_{H4}. The difference between SPF_{H2} and system efficiency is ~0.7.

It is instructive to consider the outliers. Two heat pumps achieve very high SPF_{H2}. One is an air-source heat pump that supplies underfloor heating at a maximum flow temperature of 30˚C to a highly insulated house. The SPF_{H2} is 3.90; SPF_{H4} is a little lower at 3.67. The system efficiency also includes domestic hot water heated by an exhaust air-source heat pump and immersion and is considerably lower at 2.71.

The other heat pump which achieves a very high SPF_{H2} (3.94) is a ground-source heat pump, which supplies both underfloor heating and domestic hot water to a highly insulated house. The maximum flow temperature is 31˚C for the central heating and 46˚C for the domestic hot water. SPF_{H4} is only a little lower at 3.89. The system efficiency is 3.28 indicating excellent performance.

One ground-source heat pump developed a fault and had high auxiliary electricity use. This is shown as a shaded point in the middle and bottom charts of Figure 13, but is excluded the SPF_{H4} and system efficiency columns of Table 10. SPF_{H2} is not affected by use of the auxiliary electricity and so results from this heat pump are included in the SPF_{H2} column of Table 10.

One air-source heat pump had a particularly low system efficiency, partly due to relatively high domestic hot water use (around 90%) and partly due to very long pipes and high heat losses from the tank. This point is marked as shaded on the system efficiency chart and has been omitted from the system efficiency column in Table 10.

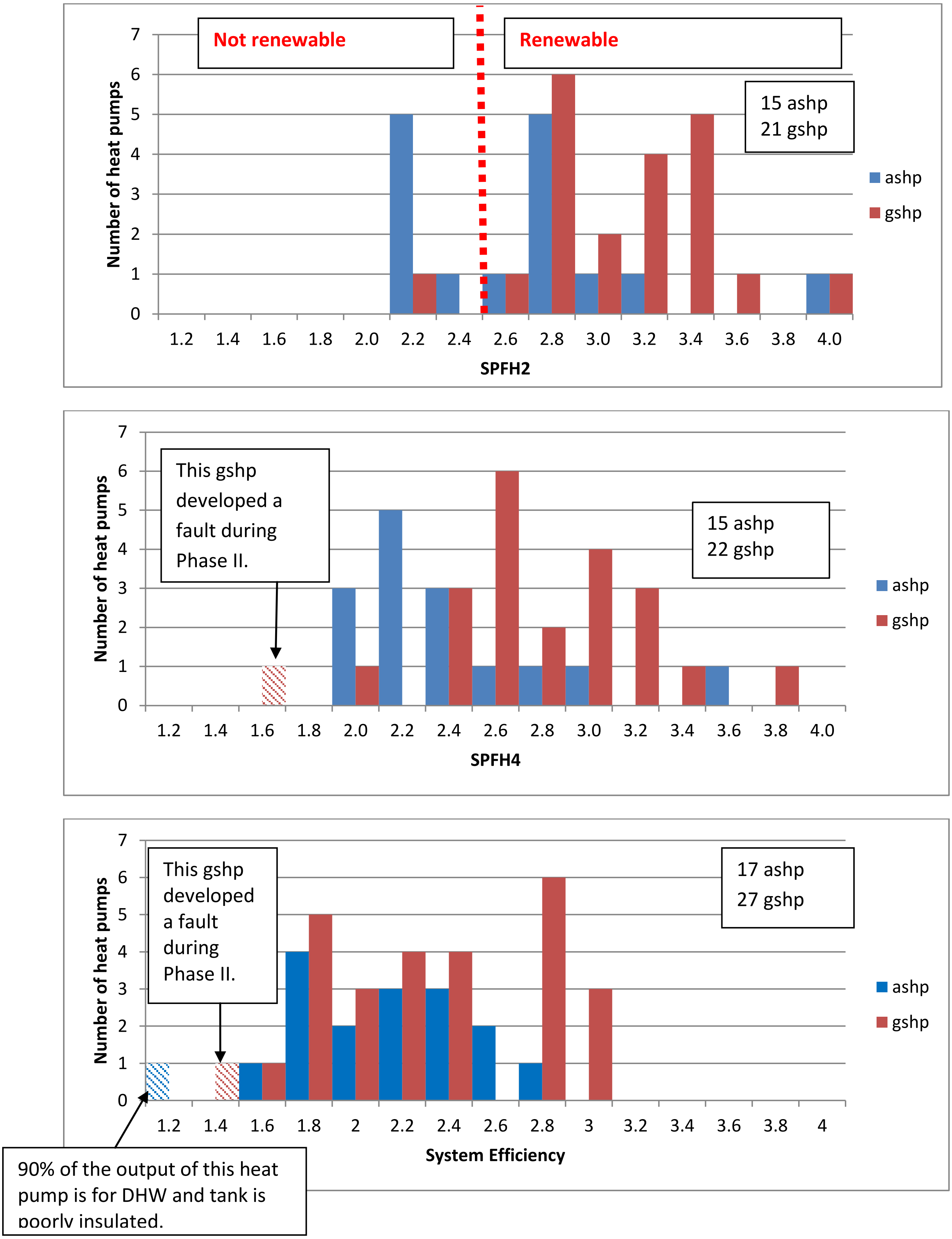
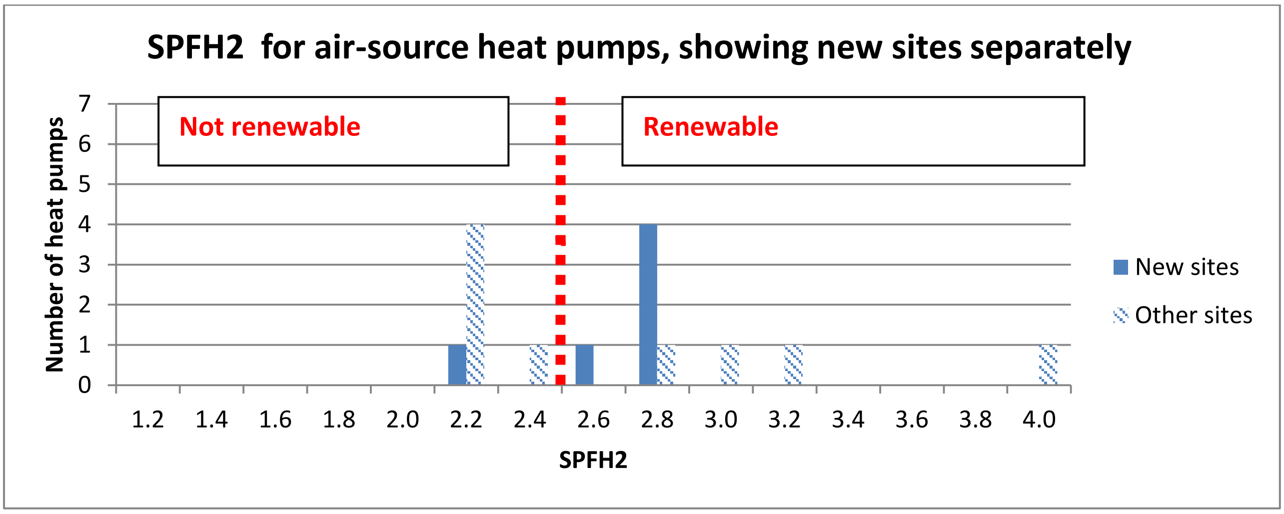


Figure 13: Comparison of SPF$_{H2}$, SPF$_{H4}$ and system efficiency for air- and ground-source heat pumps in Phase II of the trial

3.4.1. Histograms of performance for the six new air-source heat pumps

It is instructive to examine the performance of the six air-source heat pumps installed for Phase II only. All of these sites supply radiators and domestic hot water; two supply fanned radiators. Figure 14 presents SPF_{H2} and SPF_{H4} for these installations. It can be seen that five of the new sites have SPF_{H2} above the EU's criterion for renewability. SPF_{H4} figures, however, are similar to those for other air-source heat pumps in the trial.



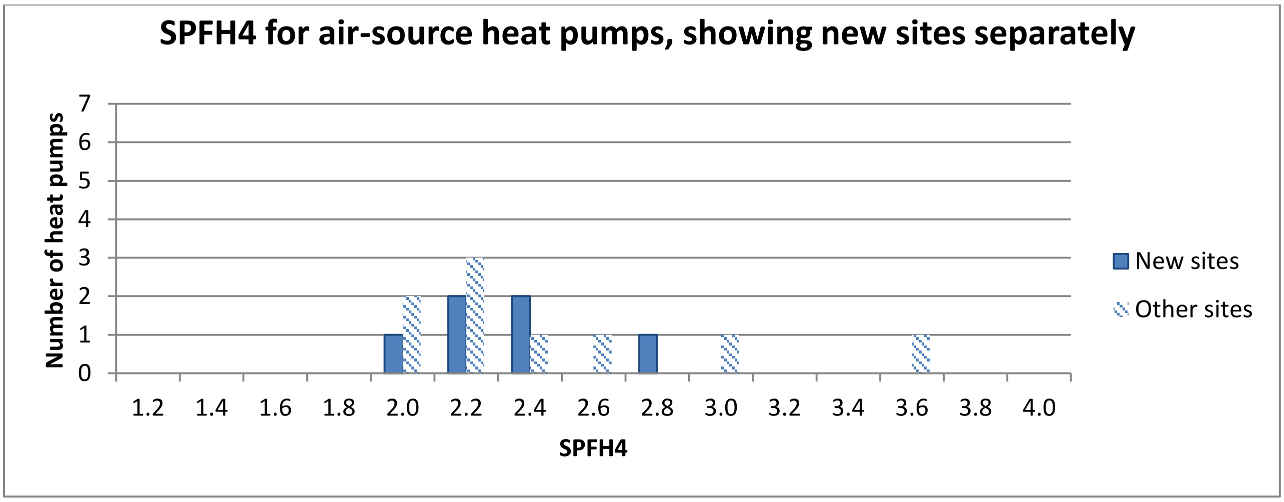


Figure 14: Comparison of SPF_{H2} and SPF_{H4} for the new air-source heat pumps in Phase II of the trial

Table 11 shows the SPF figures for each site. Only one of the five sites has an SPF_H2 below the EU RES Directive threshold to be considered renewable.

The first two systems have very good SPF_{H2}, but SPF_{H4} is compromised by the high electricity consumption of the circulation pumps and the radiator fans. This confirms the findings of section 3.1.2 that low energy circulation pumps should be used.

For sites 496-499, the difference between SPF_{H2} and SPF_H4 is low, indicating a good installation. However, in one case, the system efficiency is low; this is because a high proportion of heat is supplied to the domestic hot water tank (33%). Heat losses from the tank inevitably reduce system efficiency, even if the heat pump is working well. The same phenomenon would apply for a system with a gas boiler.

Heat pump	SPF_{H1}	SPF_{H2}	SPF_{H3}	SPF_{H4}	System efficiency	Comments
448		2.79	2.55	2.16	1.85	High use of circulation pumps and fanned radiators (19% together)
449		2.76	2.57	2.26	1.73	High use of circulation pumps and fanned radiators (21% together)
496	2.29	2.20	2.04	1.97	1.70	Domestic hot water immersion accounts for 12% of total electricity usage.
497	2.71	2.57	2.51	2.37	2.35	
498	2.94	2.79	2.62	2.48	1.81	High proportion of heat supplied to the domestic hot water tank (33%).
499	2.99	2.89	2.88	2.77	2.69	

Table 11: SPF_{H1-4} and system efficiencies for the new sites in Phase II (not temperature-corrected)

3.5. Assessment of heat pump sizing and performance

MCS MIS 3005 Issue 3.1 describes the procedure for sizing heat pumps based on the modelled heat loss of the building. With the exception of the six new sites, these detailed heat loss calculations were not carried out in this trial.

Appendix E presents the estimated SAP heat losses and the measured heat losses for a selection of sites in the trial.

It would be instructive to examine the SPF_{H4} figures during periods of cold temperature for any under-sized sites. In practice, this analysis can not be undertaken, since SPF_{H4} was not calculated during Phase I and there were very few cold days during the Phase II monitoring period.

3.6. Histograms of space and water heating efficiencies

Six of the 44 sites supplied only space heating, while the remaining 38 supplied both space and water heating. In 11 cases, the complexity of the systems, or faults with heat meters meant that it was not possible to produce separate estimates of space and water heating efficiencies. However, for the remaining 27 sites, careful examination of the time series enabled separate estimation of the efficiencies for space and water heating.

Table 12 summarises the number of sites for which space and water heating efficiencies can be calculated. Efficiencies are presented as SPF_{H2}, **i.e. they do not include the effect of electric immersion or circulation pumps on the central heating side.**

	SPF_{H2}			
	Space heating (all sites)	Water heating	Sites for which both space and water heating can be calculated	
			Space heating	Water heating
Number of sites	34	27	27	27
Of which air-source	*14*	*11*	*11*	*11*
Of which ground-source	*20*	*16*	*16*	*16*
Mean	3.01	2.43**	3.10	2.43 **
Standard deviation	0.49	0.62	0.46	0.62 **
Range	2.13-4.6	1.64-4.20**	2.13-4.6	1.64-4.2 **

Table 12: Space and water heating efficiencies from Phase II (as SPF_{H2})

** These values are influenced by an outlier, as discussed below.

The third and fourth columns of Table 12 show the space and water heating efficiencies (as SPF_{H2}) for the 27 sites for which it is possible to calculate both. The same information is shown visually in Figure 15.

Of these sites, 11 were air-source and 16 ground-source. The Figure shows a wide range of efficiencies for both space and water heating, but, on average, space heating is more efficient with a mean SPF_{H2} of 3.01 ± 0.08, as compared to the mean SPF_{H2} for water heating, which is 2.43 ± 0.12; however, this includes one outlier; if this value is removed, the average SPF_{H2} for water heating is 2.36 ± 0.10.

Space and water heating are discussed in more detail in the following sections, but this preliminary analysis indicates that heat pumps can be configured to heat water efficiently.

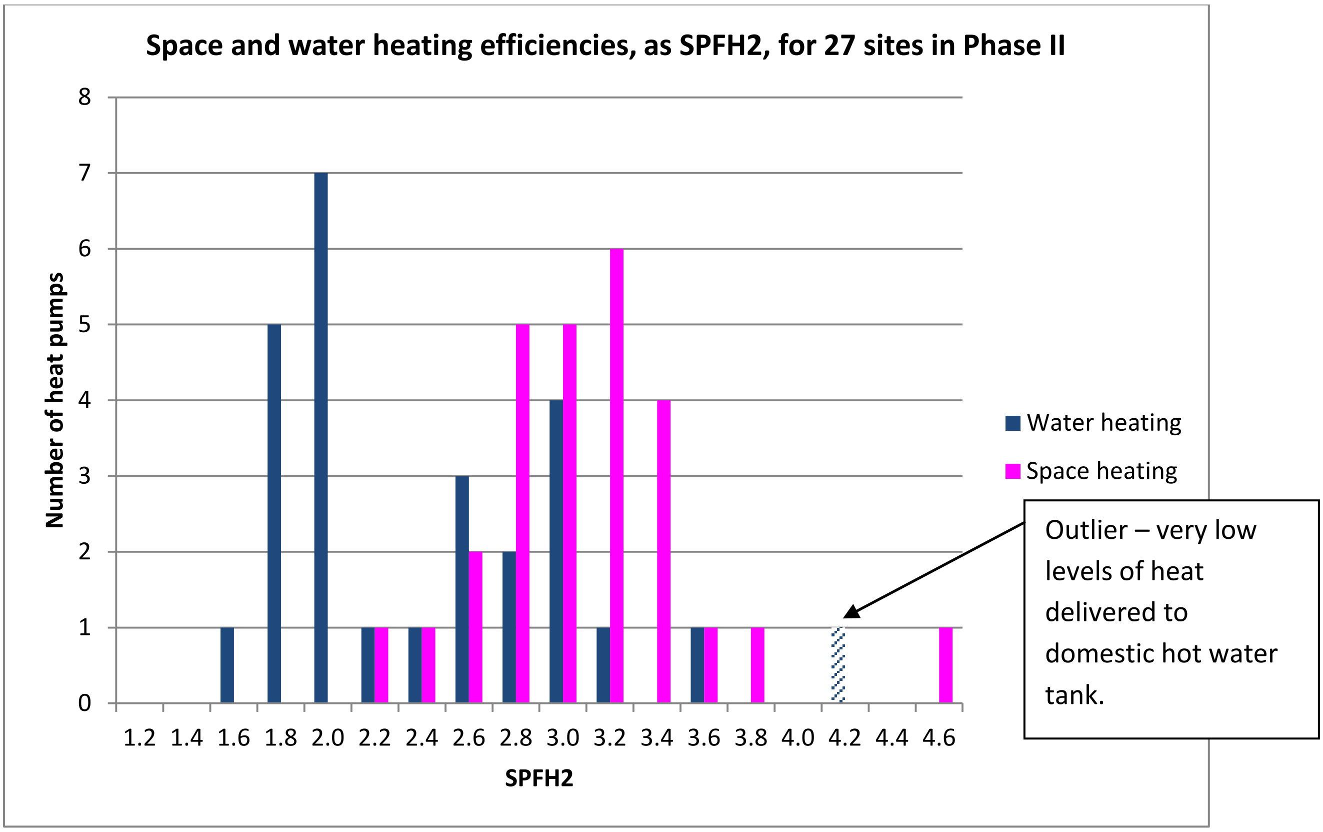


Figure 15: Space and water heating efficiencies as SPF_{H2} for 27 heat pumps, Phase II

3.6.1. Space heating efficiency for air and ground-source heat pumps

Space heating efficiencies, as SPF_{H2}, can be estimated for 34 sites. Table 13 and Figure 16 show space heating efficiencies (as SPF_{H2}) for ground and air-source heat pumps. There is one outlier, with a space heating efficiency of 4.6. This was a ground-source heat pump which supplied underfloor heating to a highly insulated dwelling. Central heating flow temperatures at this site were between 30 and 35˚C throughout the heating season.

Note the very small sample sizes (15 air-source heat pumps and 20 ground-source). On average, the ground-source heat pumps showed high space heating efficiencies (as measured by SPF_{H2}). Note that this remains true even if the particularly efficient site is removed.

	Space heating efficiency (as SPF_{H2})	
	Air-source	Ground-source
Number of sites	14	20
Mean	2.73	3.21
Standard deviation	0.34	0.46
Range	2.2-3.2	2.2-4.6

Table 13: Space heating efficiencies for air- and ground-source heat pumps (as SPF_{H2})

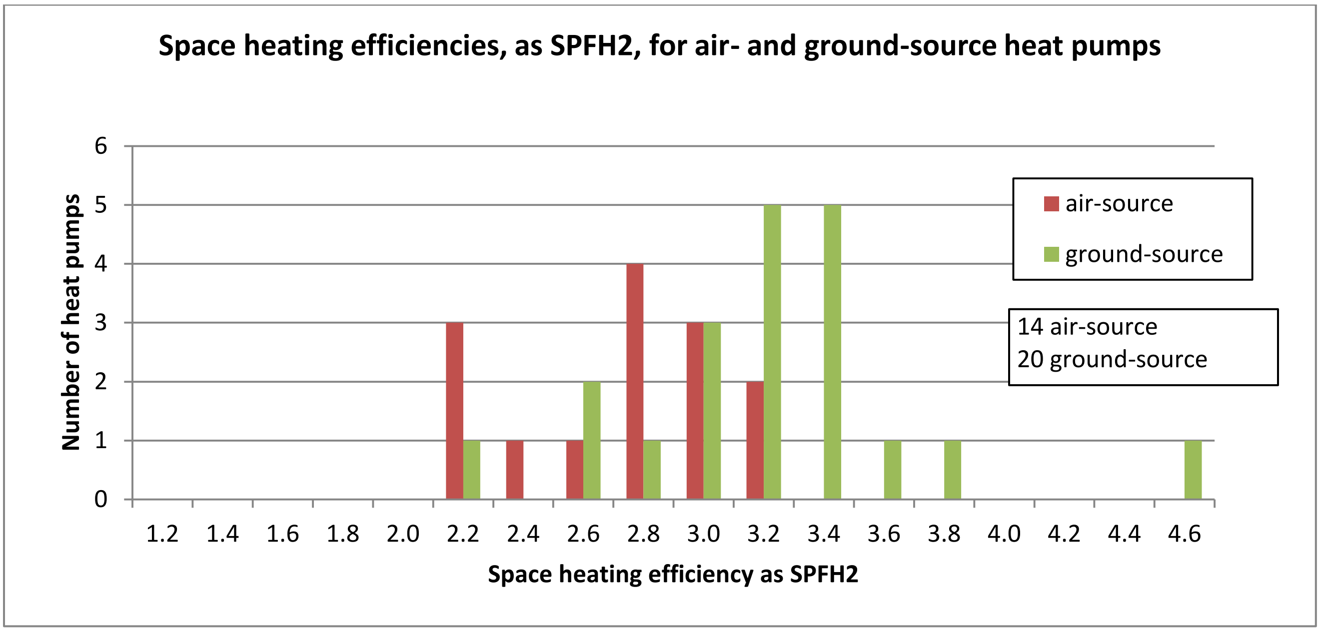


Figure 16: Space heating efficiencies for 14 air- and 20 ground-source heat pumps (as SPF_{H2})

Figure 17 shows the space heating efficiency for all sites, as a function of heat delivered during the heating season. There is a great deal of scatter, but it appears that there is a slight drop off in efficiency of ground-source heat pumps at low annual heat demands (below around 5,000 kWh). The efficiency stabilises at higher levels of heat delivery.

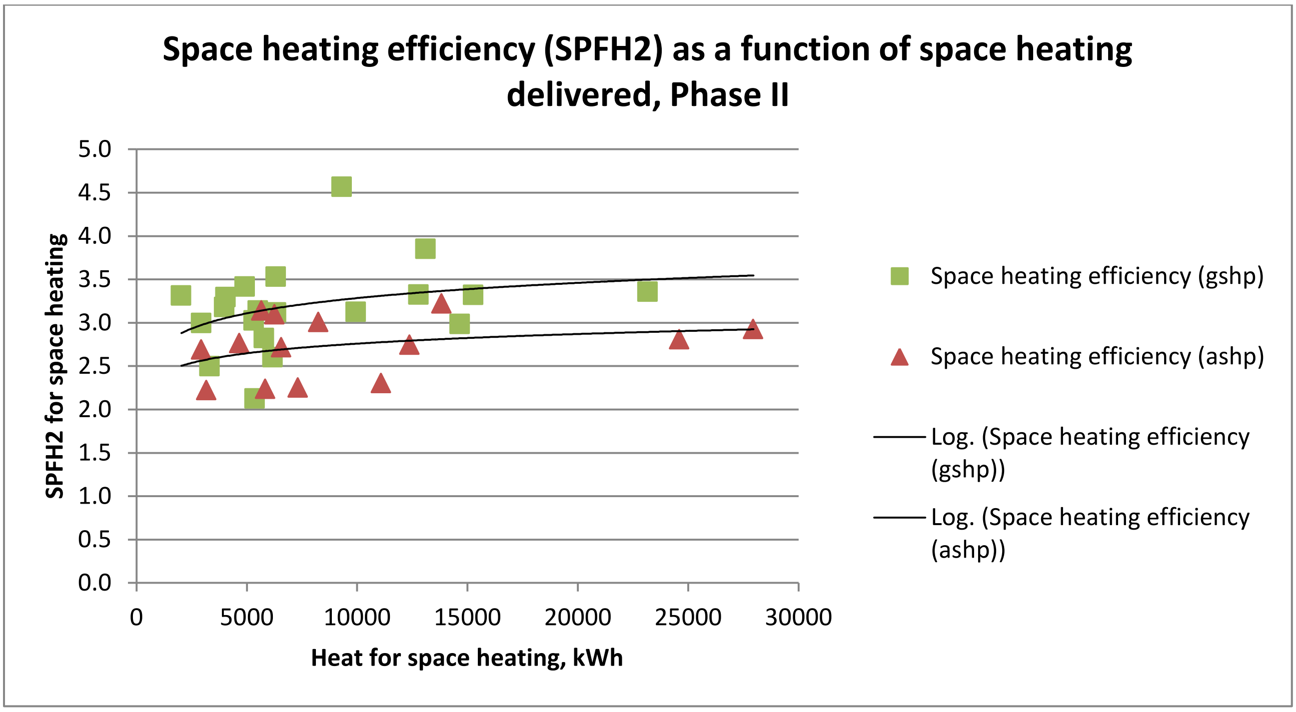


Figure 17: Space heating efficiency as a function of space heating delivered for Phase II sites

3.6.2. Space heating efficiency as a function of flow temperature

Space heating efficiency is expected to be inversely proportional to the central heating flow temperature. Most of the sites in the trial used weather compensation control algorithms. In some cases, the range of flow temperatures was very large (20 degrees or so), while in others, it was relatively limited (10 degrees or so).

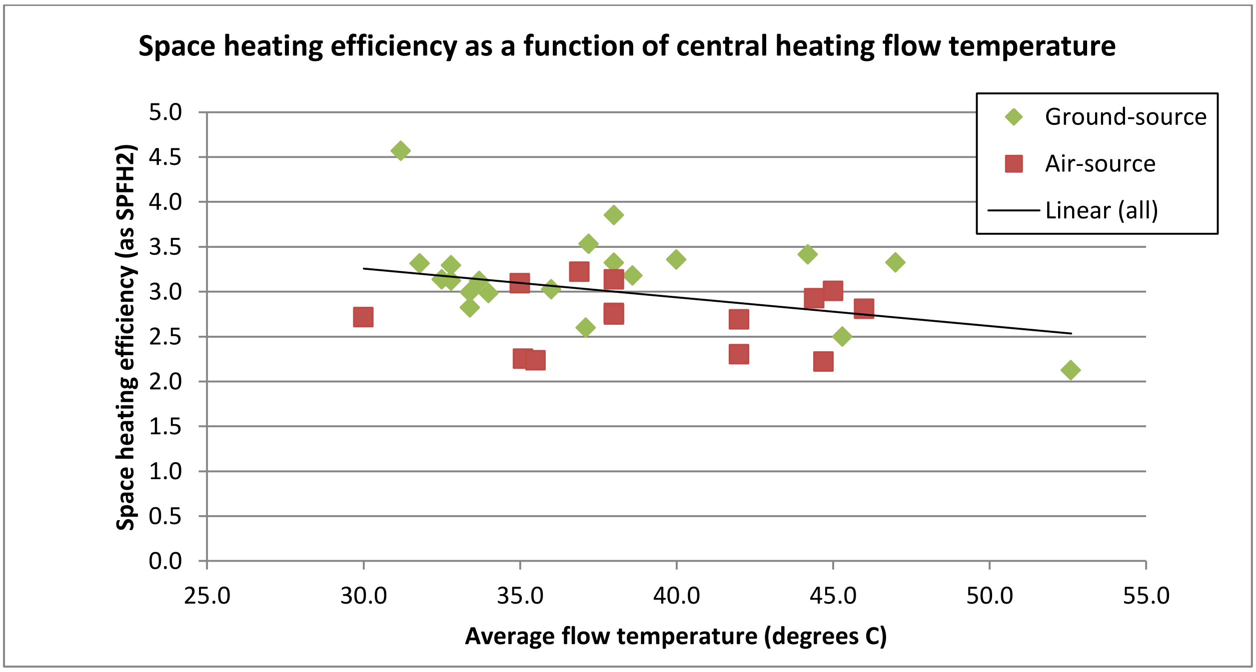


Figure 18 shows the average space heating efficiency (as SPF_{H2}) as a function of the mode of the central heating flow temperature. There is a great deal of scatter, but, overall, the chart shows the expected decrease in space heating efficiency as central heating flow temperatures increase.

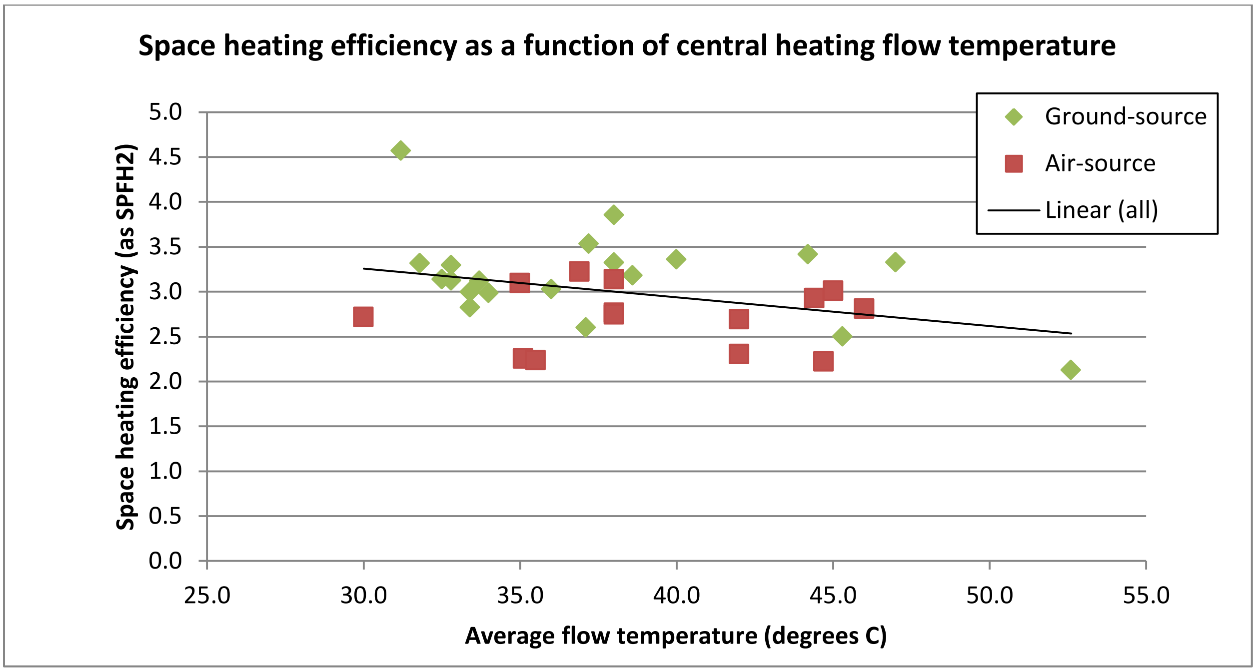


Figure 18: Space heating efficiency as a function of central heating flow temperature for Phase II sites

The case studies presented in sections 5-8 show individual charts of efficiency as a function of daily average ambient temperature.

3.6.3. Water heating efficiency

Table 14 and Figure 19 show water heating efficiencies (as SPF_{H2}) for ground- and air-source heat pumps. **Note the very small sample sizes (11 air-source heat pumps and 16 ground-source)**.

	Water heating efficiency (as SPF_{H2})	
	Air-source	Ground-Source
Number of sites	11	16
Mean	2.51	2.35
Mean if outlier air source heat pump removed	2.34	2.35
Range if outlier air-source heat pump removed	1.8-3.2	1.6-3.6

Table 14: Water heating efficiencies for air- and ground-source heat pumps (as SPF_{H2})

One air-source heat pump has a very high efficiency for heating water (4.2). These data points were checked and found to be correct; however, the SPF_{H2} figure reflects the heating efficiency without the hot water immersion. For this site, only 364 kWh of heat was transferred from the heat pump to the tank and the remaining 4199 kWh was provided by the immersion. The water heating SPF_{H4} figure is close to 1.

If this point is omitted, then the SPF_{H2} water heating efficiencies of ground and air-source heat pumps in the trial are found to be the same, i.e. around 2.35. This is substantially lower than the space heating efficiencies recorded in section 4.4.1; however, an SPF_{H2} of 2.35 indicates that the heat pump is supplying the domestic hot water tank efficiently, although many of these systems also use the electric immersion to heat the domestic hot water tank.

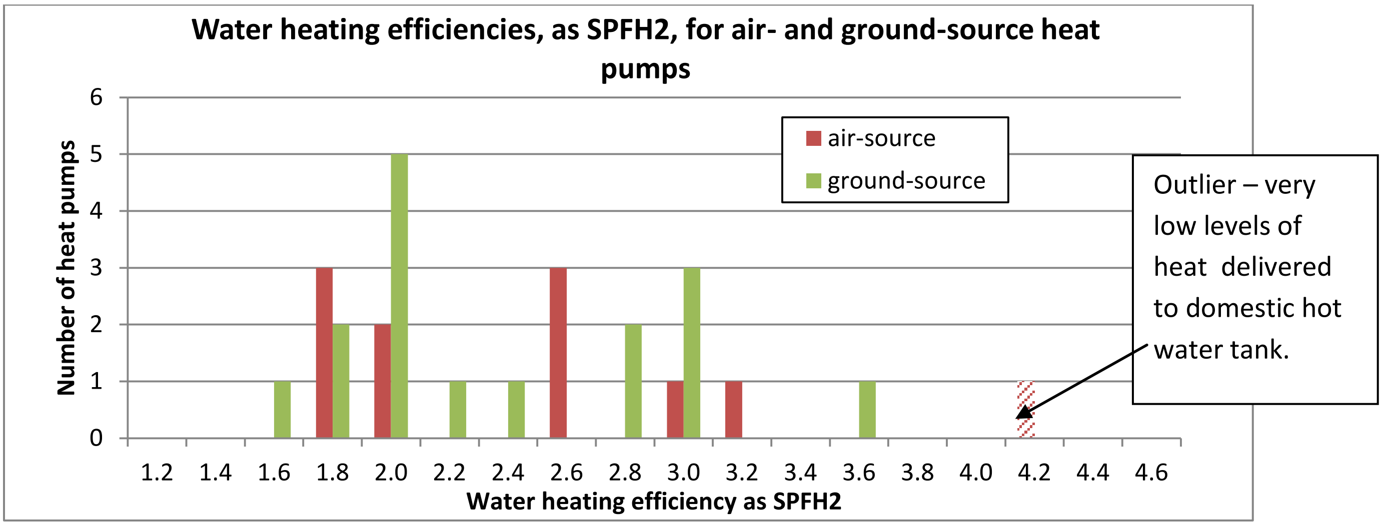


Figure 19: Water heating efficiencies for 11 air- and 16 ground source heat pumps (as SPF_{H2})

We would expect the efficiency of water heating to be strongly influenced by the temperature at which the domestic hot water is stored. Table 15 shows the efficiency of water heating (as SPF_{H2}) as a function of the average temperature of the domestic hot water tank (excluding periods of sterilisation). The comparison is not perfect, since the immersion is used in many cases and this is not included in SPF_{H2}; however, the table does show, as expected, that two of the highest water efficiencies detected in the trial refer to sites where the domestic hot water tank is kept at a very low temperature (30-40 degrees).

Water heating efficiency, as SPF_{H2}	Temperature of domestic hot water tank (˚C)		
	30-40	40-50	50-60
1.5-2.0		6	1
2.0-2.5		3	2
2.5-3.0	1	4	1
3.0-3.5	1		
3.5-4.0		1	

Table 15: Water heating efficiencies (as SPF_{H2}) as a function of temperature of domestic hot water tank

There is a weak correlation (R^2=0.33) between the water heating efficiency and the amount of heat delivered, as shown in Figure 20.

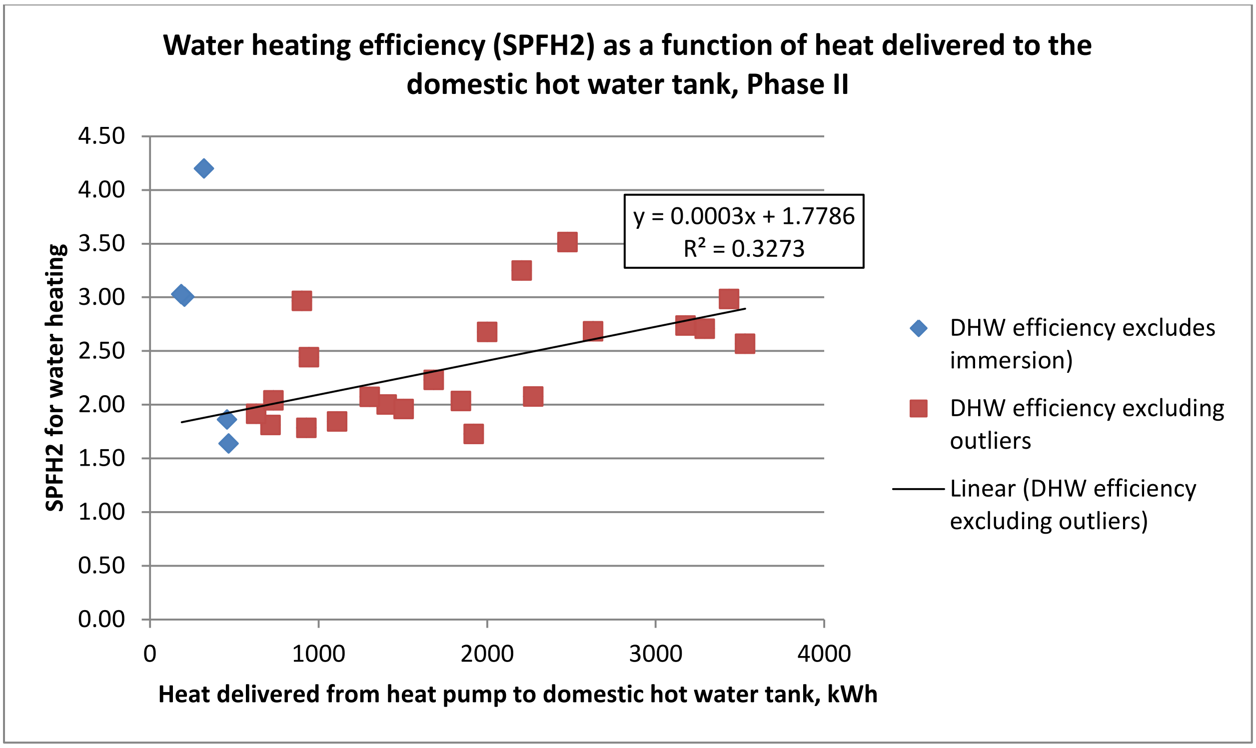


Figure 20: Water heating efficiency (as SPF_{H2}) as a function of heat delivered from the heat pump to the domestic hot water tank

3.6.4. Summary

The analysis presented in this section demonstrates that, for the heat pumps in phase II of the trial:

- Space heating efficiencies are greater for the ground-source heat pumps than for the air-source heat pumps (average SPF_{H2} = 3.21 and 2.73 respectively).
- For ground-source heat pumps, space heating efficiencies are slightly lower for sites with small heat demands (< 5,000 kWh/year) but appear to stabilise above this level. This may be due to excessive cycling if heat pumps are over-sized for the heat demand. More investigation would be needed to confirm this.
- On average, water heating efficiencies are lower than space heating efficiencies, being around 2.35 for both air- and ground-source (as measured by SPF_{H2}).
- Water heating efficiency (as measured by SPF_{H2}) increases with heat supplied to the domestic hot water tank.

- For some individual sites, water heating efficiencies may be higher than annual space heating efficiencies; this is because the amount of energy used for water heating is roughly constant throughout the year, but space heating load increases with ambient temperature, while space heating efficiency decreases with ambient temperature.
- The highest water heating efficiencies in the trial (as SPF_{H2}) are found for sites where the water is stored at unsatisfactorily low temperatures.

4. Case Studies (Major changes)

This section shows some examples of sites where major interventions were carried out between Phases I and II.

This section shows some examples of sites for which interesting behaviour has been observed and from which key recommendations can be made. Where possible, SPF_{H1}-$_{H4}$ and system efficiency have been calculated. In addition, temperature-corrected system efficiencies (for the 20 year period 1987 to 2006) are also presented.

4.1. Air-source Heat Pump Supplying Radiators Only, Site 444

At this site, which is a two bedroomed bungalow, an air-source heat pump supplies heat to radiators only, see Figure 21.

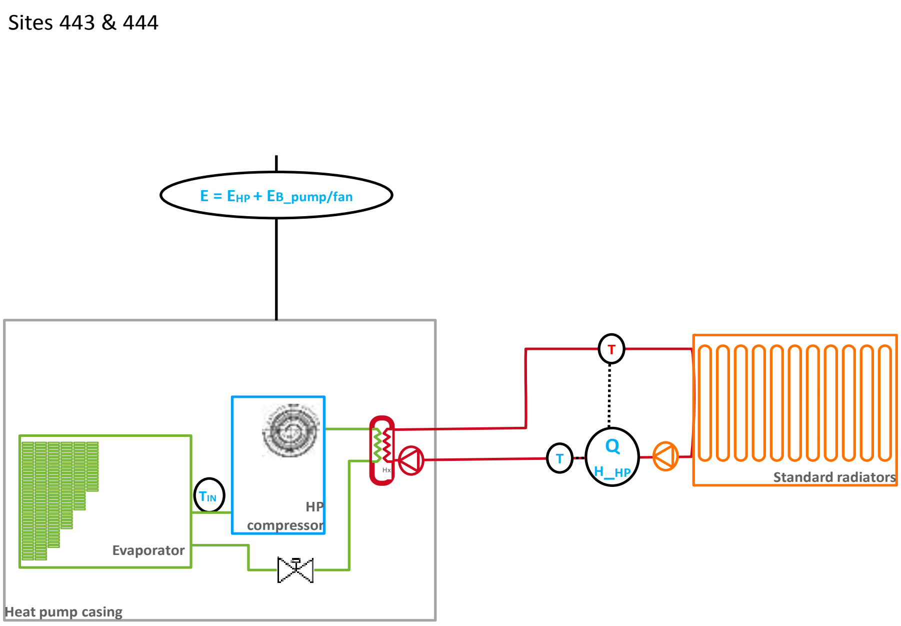


Figure 21: Schematic for site 444, Phase II

The average heat loss coefficient of the property was found to be 176 W/K. The 6 kW heat pump should have been able to supply the 3.9 kW required to heat the property at the MCS guideline temperature conditions. However, it was decided to replace the existing 6 kW air source heat pump by an 8 kW air source heat pump. This would be expected to increase cycling, so the temperature differential in the control system was increased from 3°C to 5°C to offset this effect. The householder changed the heating pattern from intermittent to continuous.

Weather compensation was not deployed in Phase I but was in Phase II. The defrost sensor was also replaced and repositioned in an attempt to reduce the amount of defrost. Sections 4.1.1-4.1.4 discuss the effect of these changes on seasonal performance factor, operational hours, cycling and the energy used for defrost.

4.1.1. SPFH1-4 and System Efficiency

The overall effect on seasonal performance factor is shown in Table 16 and Figure 22. Note that there was some faulty heat meter data in April 2011 and so this month has been excluded from the calculation of SPF's.

	Dates	SPF_{H1}	SPF_{H2}	SPF_{H3}	SPF_{H4}	System efficiency	Temperature corrected system efficiency
Phase I	01/04/2009-31/03/2010	N/A	N/A	N/A	1.63	1.63	1.63[9]
Phase II	01/05/2011-31/03/2012	(3.20)	(2.44)	(2.44)	2.24	2.24	2.19

Table 16: Seasonal performance factors and system efficiency for site 444, Phases I & II

N/A = relevant monitoring not carried out, so this parameter cannot be calculated.

Figures in brackets have been estimated by examining the time series of electricity demand to estimate the electricity used by the inlet fan and by the circulation pump on the central heating side.

The table also illustrates the effect of using different system boundaries when defining performance. For this site, there is no domestic hot water provision, so the system efficiency is the same as SPF_{H4}.

[9] There has been a slight re-adjustment in the reported system efficiency since the first year results were published, due to removal of a small amount of faulty data. Note that temperature corrections may vary for different sites, depending on a) the amount of data recorded and b) the local degree days. For this site, the temperature correction was zero in Phase I.

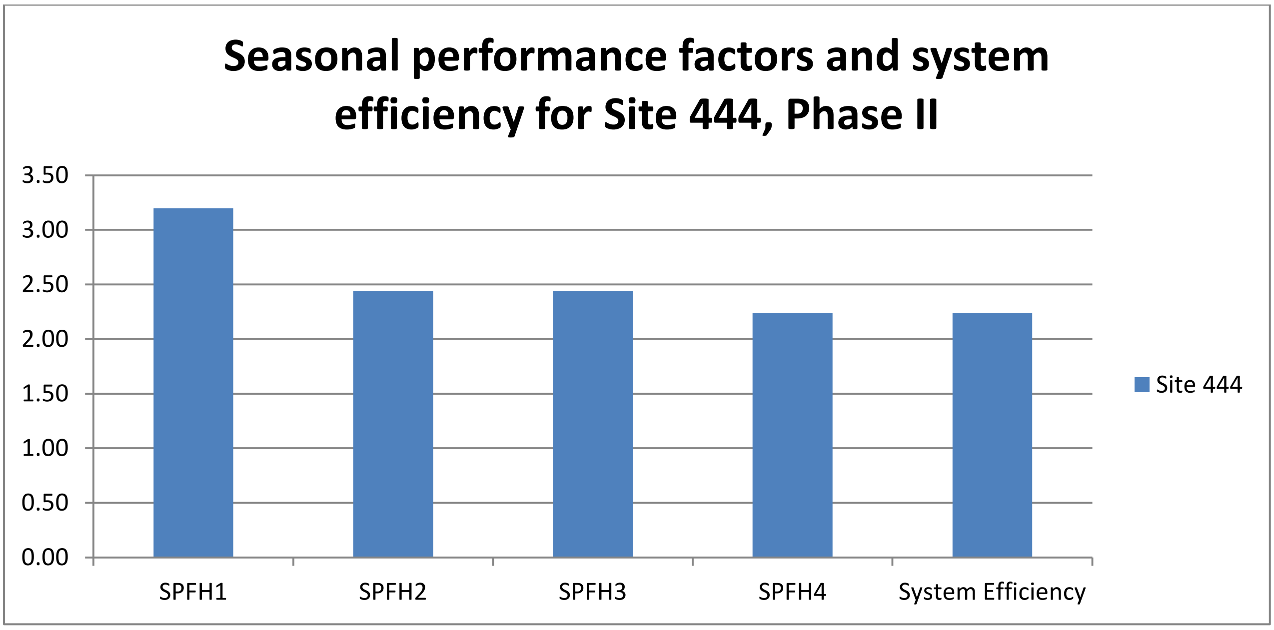


Figure 22: Seasonal performance factors and system efficiency for site 444, Phase II

Figure 23 shows the effect of the changes on the overall seasonal performance factor, SPF_{H4}, for this site, as a function of daily average ambient temperature. The seasonal performance factor is improved at all ambient temperatures, but particularly at higher temperatures (5-15°C), reflecting the effect of the change in weather compensation for this site.

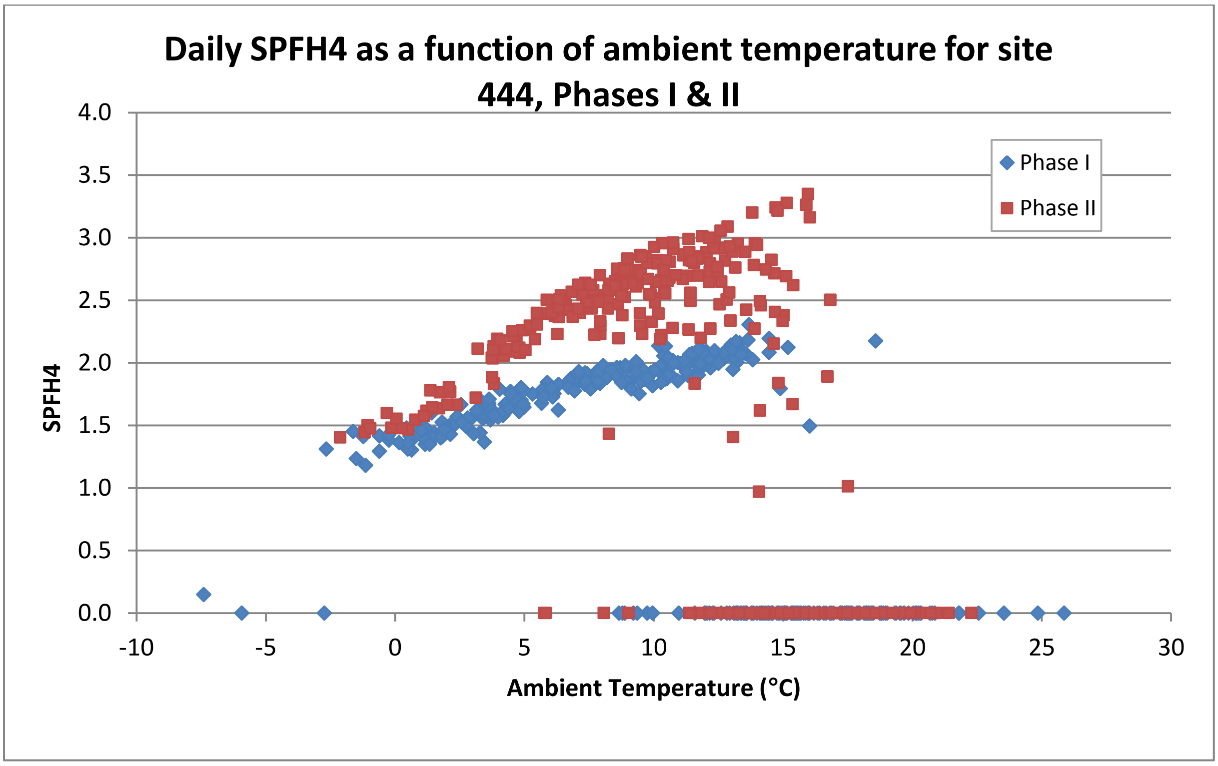


Figure 23: Daily SPF_{H4} as a function of daily average ambient temperature for site 444, Phases I & II

4.1.2. Operational Hours

In the first phase of the trial, the householder used the heat pump intermittently, for between 2 and 7 hours per day, while in Phase II, the heat pump was set to continuous operation. Figure 24 - Figure 25 illustrate the operating patterns schematically. As a result, daily average internal temperatures increased. During Phase I, the average internal temperature in the living room was between 15 and 20°C during the heating season, while in Phase II, it was much more constant, between 18 and 20°C. The number of degree days for the Phase II heating season was 25% lower than that for Phase I (partly because of the exclusion of faulty heat meter data from April 2011). However, the change to continuous heating meant that the heat used in Phase II was only 7% lower than that in Phase I, while improved performance meant that the electricity used was 32% lower than in Phase I, see Table 17.

	Heat Output (kWh)	Electricity input (kWh)	Degree days	Heat supplied / degree day
Apr-09 to Mar-10	4206	2574	2057	2.04
May-11 to Feb-12[10]	3925	1755	1541	2.54

Table 17: Degree day heating requirements and actual heat supplied, site 444, Phases I & II

[10] Faulty heat meter data in April 2011 so period runs from 01/05/2011 to 28/02/2012

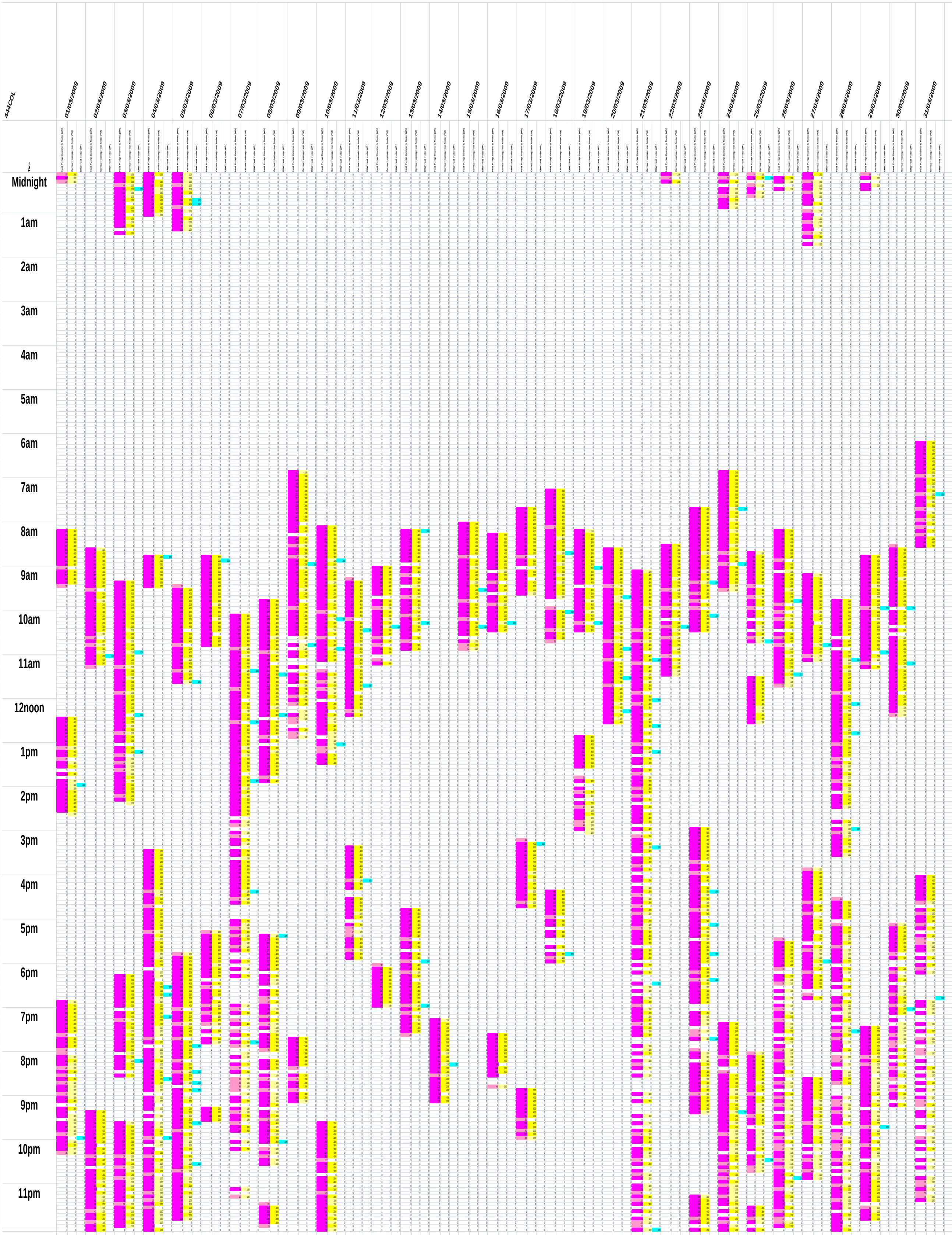


Figure 24: Tapestry of operational hours for site 444 in Phase I (March 2009)

The tapestry chart above represents one calendar month. Each vertical line shows a single day, with the hours of the day down the left-hand side. Pink shading indicates that the system is using electricity; yellow shading shows that heat is being produced and the light blue indicates DHW use.

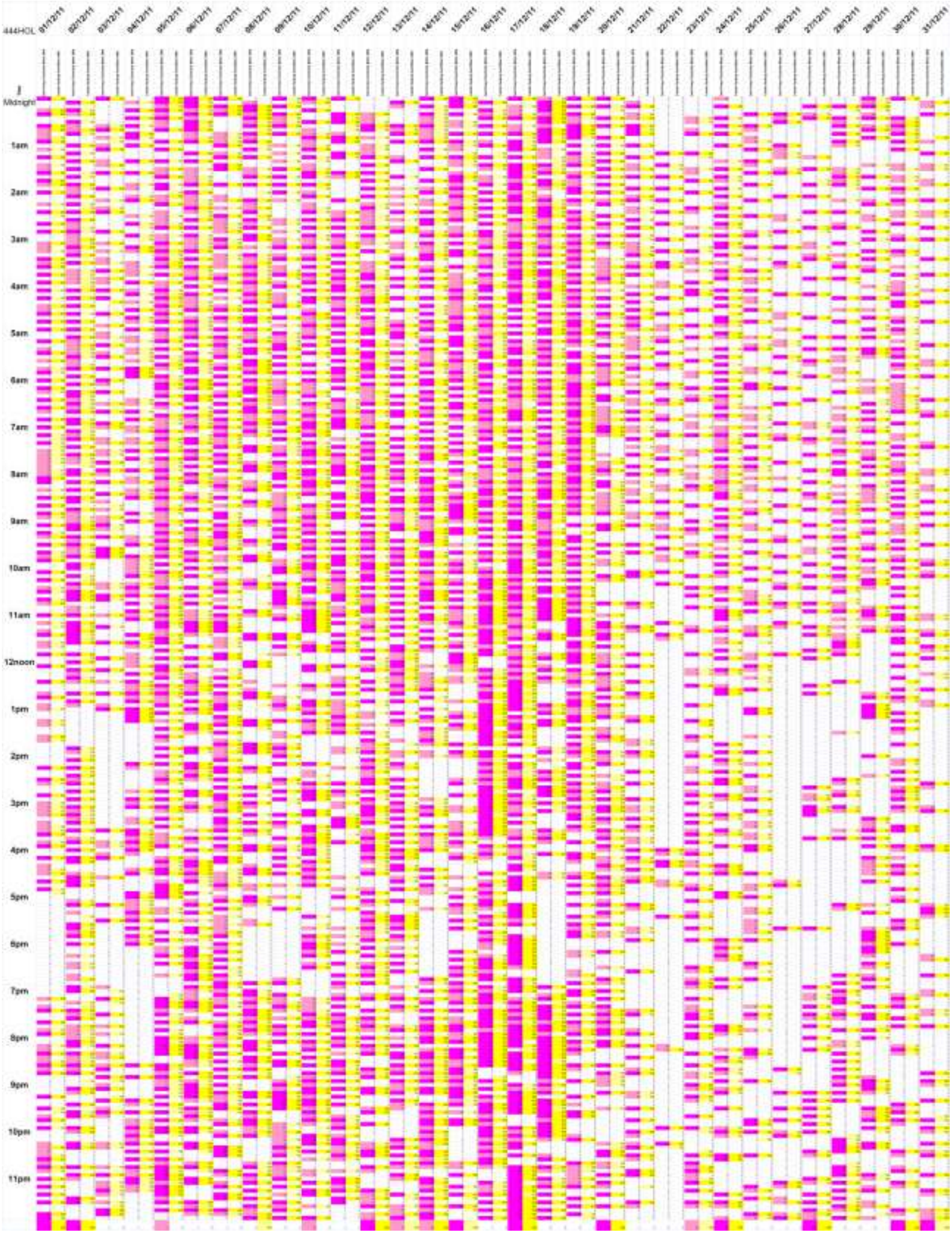


Figure 25: Tapestry of operational hours for site 444 in Phase II (December 2011)

4.1.3. Cycling

Cycling is observed in both phases, (see Figure 26 - Figure 27). It appears that cycling increases during the second phase, due to the use of a larger heat pump for longer periods of time and this is not offset by the change to the controls. It is important to note that the sampling period (5 minutes) is comparable to the cycling period, which explains the ragged appearance of the charts. A shorter sampling period, e.g. 1 minute, would be required to allow the cycling rate to be estimated.

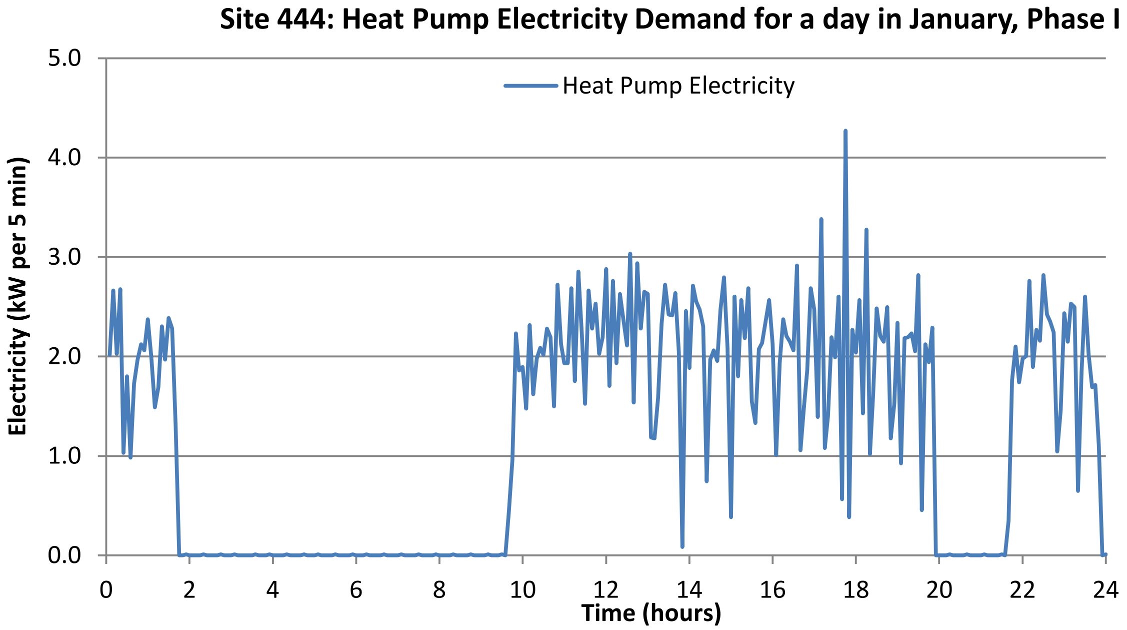


Figure 26: Electricity demand by heat pump 444 for a day in January 2010 (Phase I)

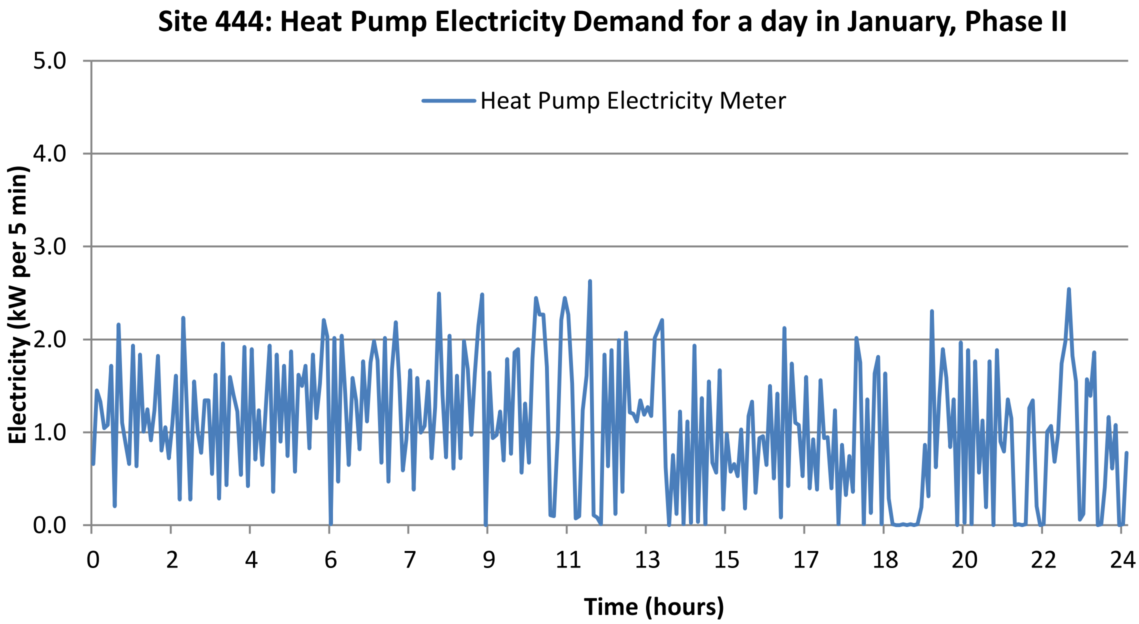


Figure 27: Electricity demand by heat pump 444 for a day in January 2012 (Phase II)

4.1.4. Defrost

One of the modifications carried out at this site was to attempt to reduce unnecessary defrosting by moving the external temperature sensor to a new location.

Figure 28 shows a time series of the daily heat used for defrost in kWh for the period February 2009 to March 2012. There is a clear increase in the amount of energy being used for defrost over this period, on some days as much as 14 kWh per day of defrost is used (which is around 1.5 times the domestic hot water consumption of the average family). This is not due to colder weather; the winter of 2011-12 was milder than the winter of 2009-10, but the energy used for defrost was significantly higher in 2011-12 than in 2009-10, see Table 18 and Figure 29. It appears that the relocation of the external temperature sensor has not been successful in reducing the amount of defrost. This could be due to humidity; the greatest use of energy for defrosting occurs when the evaporator temperature is just below zero (i.e. the ambient temperature is just above zero and the humidity is high).

If there were no defrost, SPF_{H4} would be improved from 2.24 to 2.4. This example illustrates the importance of monitoring the energy used for defrost.

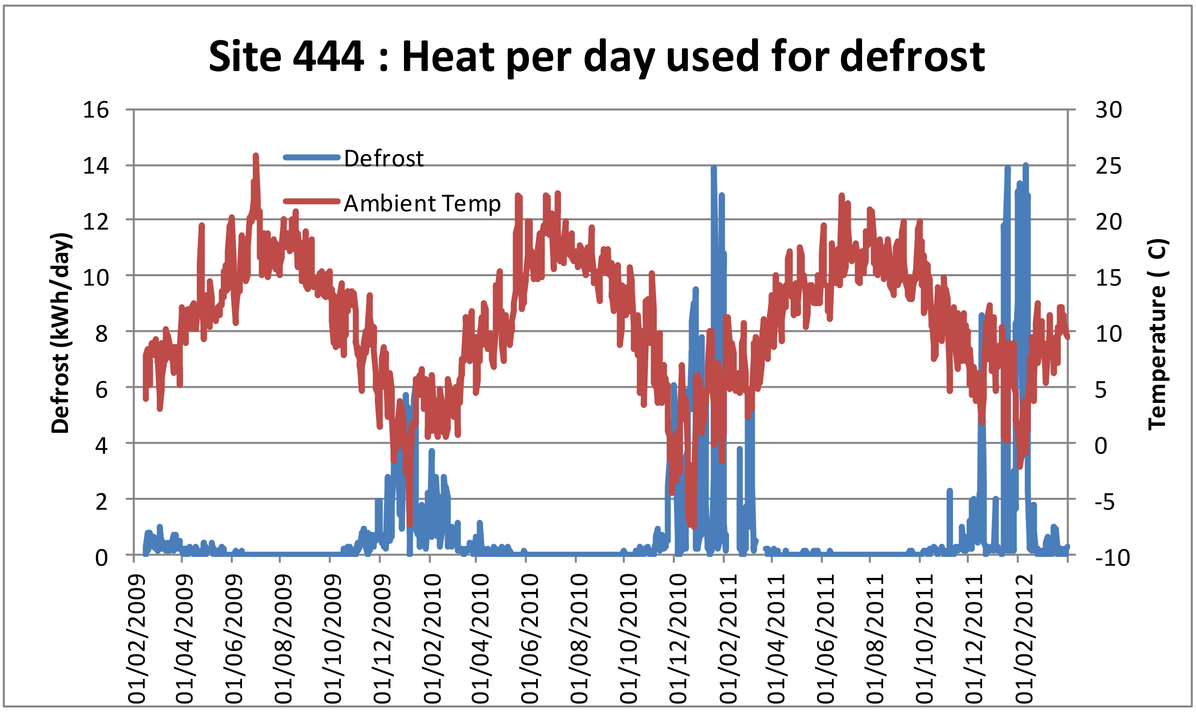


Figure 28: Ambient temperature and daily heat used for defrost at site 444, Phases I & II

	Phase I	Phase II
Dates	01/04/2009-31/03/2010	01/04/2011-31/03/2012
Energy used for defrost, kWh	200	294

Table 18: Heat used for defrost, site 444, Phase I & II

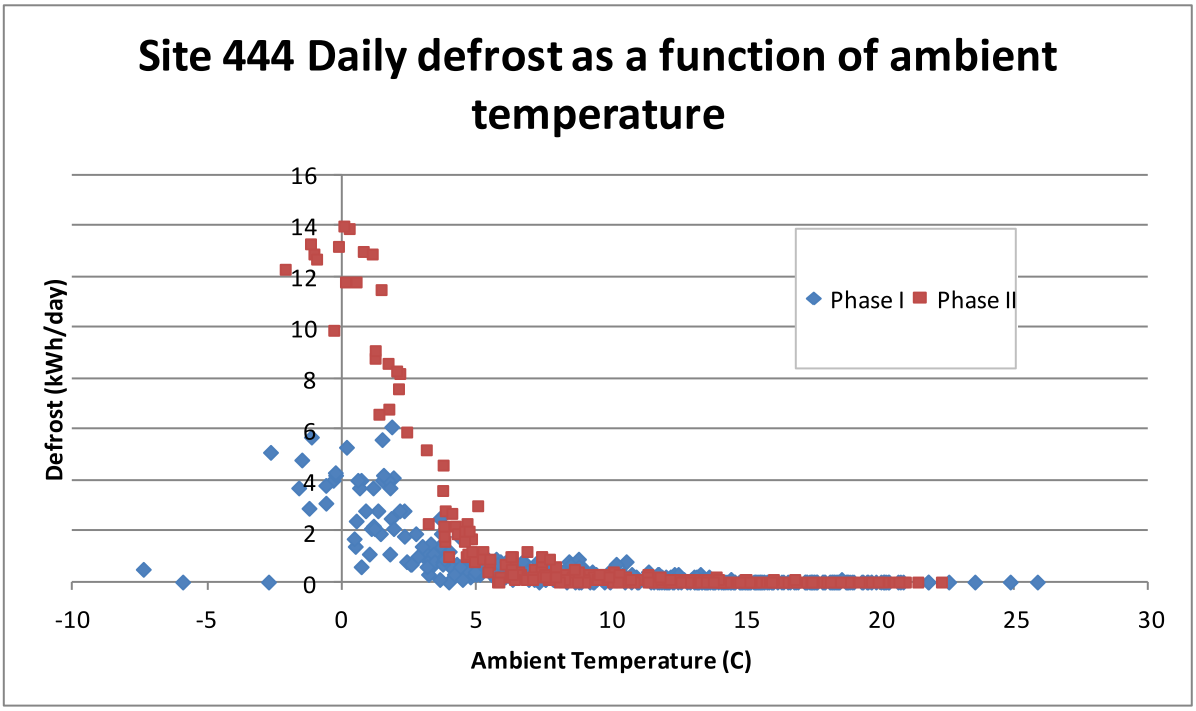


Figure 29: Daily defrost as a function of ambient temperature at Site 444, Phases I & II

4.2. Ground-source Heat Pump Supplying Radiators and Domestic Hot Water, Site 461

At this site, a 3.5 kW ground-source heat pump supplies radiators and domestic hot water for a semi-detached bungalow. The heat pump was replaced by a newer model with the same rated power and the level of loft insulation in the house was increased. The schematic is shown in Figure 30.

Sites 460 & 461

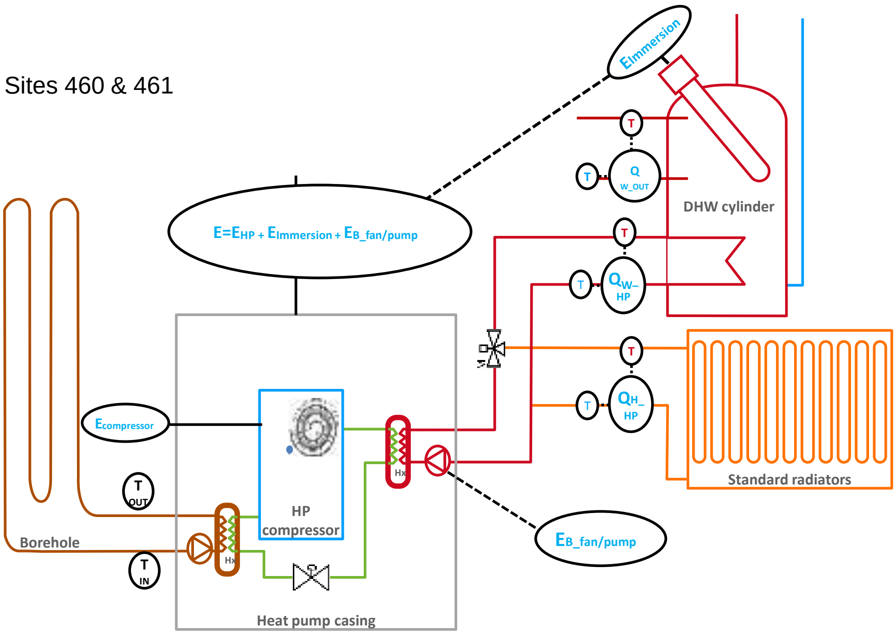


Figure 30: Schematic for site 461, Phase II

4.3.1. SPFH1-4 and system efficiency

Table 19 shows SPF_{H1-H4} and system efficiencies for Phases I and II.

	SPF_{H1}	SPF_{H2}	SPF_{H3}	SPF_{H4}	System efficiency	Temperature corrected system efficiency
Phase I	N/A	3.18	3.18	3.00	2.56	2.34
Phase II	(4.08)	3.66	2.54	2.43	2.17	2.09

Table 19: Seasonal performance factors and system efficiencies for site 461, Phase I & II

Figure 31 shows a significant improvement in SPF_{H2} after the intervention (from 3.18 to 3.66). However, the improvement in SPF_{H2} does not translate into an improved performance overall SPF_{H3}, which includes the electric immersion to the domestic hot water tank[11], falls from 3.18 in phase I to 2.54 in Phase II (see Table 19 and Figure 32). The circulation pumps on the central heating side reduce SPF_{H4} to 2.43, while the householders' low consumption of domestic hot water reduces the system efficiency to only 2.17.

[11] There is no auxiliary electric space heating for this design of heat pump. If there were, it would be included in SPF_{H3}.

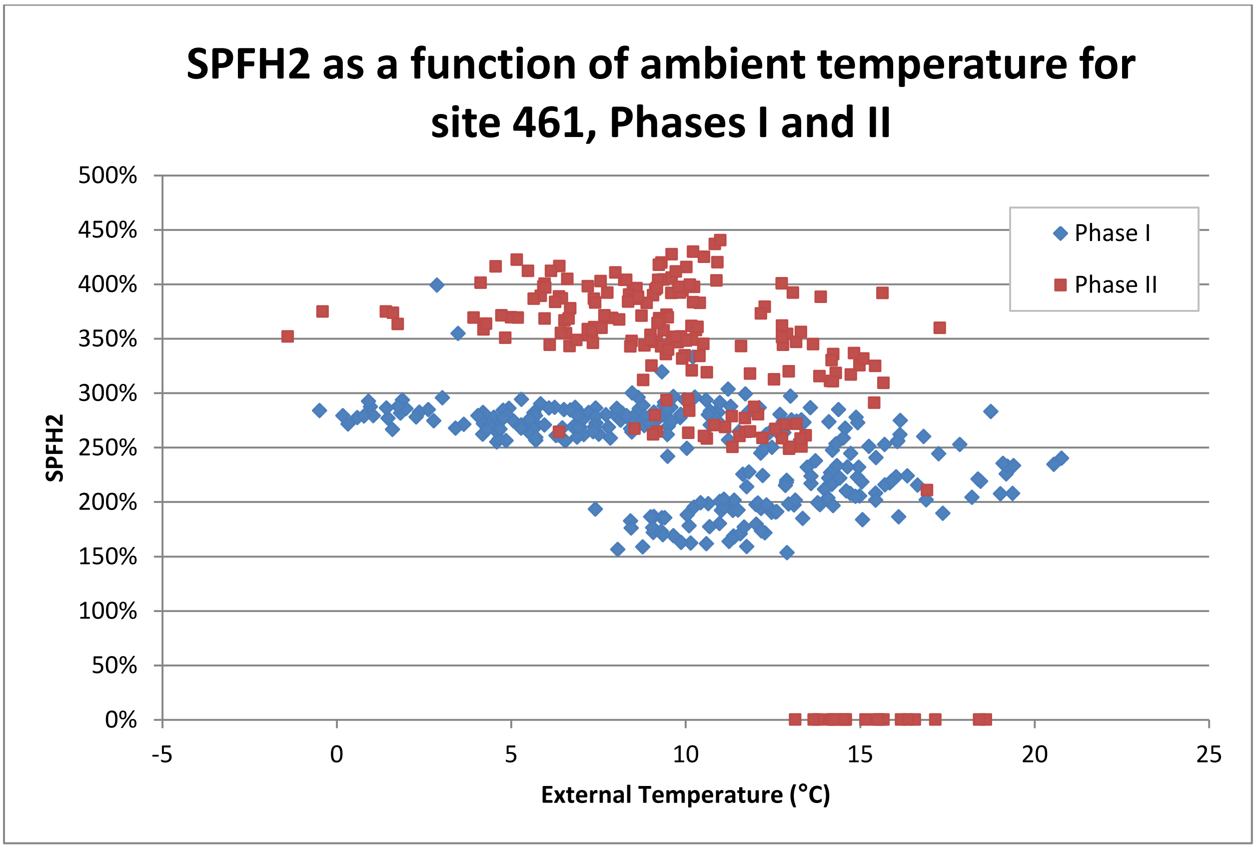


Figure 31: SPFH2 as a function of ambient temperature, site 461, Phases I & II

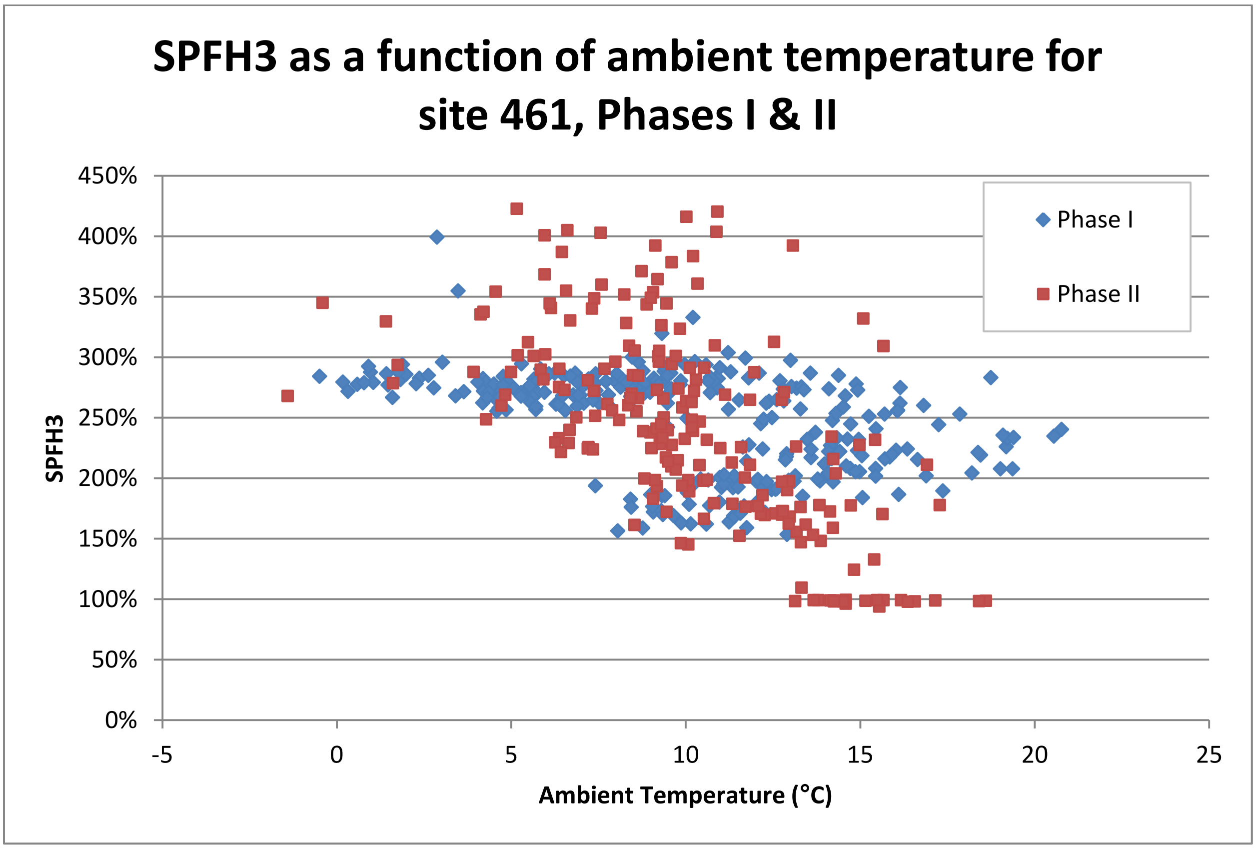


Figure 32: SPF_{H3} as a function of ambient temperature for site 461, Phases I & II

The heat pump was designed to use a refrigerant that enables production of domestic hot water at suitable temperatures, obviating the need for immersion. However, in this case, the householder preferred very hot domestic hot water and used the immersion in the second phase of the trial. Figure 33 and Figure 34 show that the proportion of electricity supplied to the immersion increased from 0% in the first phase to 37% (861 kWh) in the second. It should be noted that this behaviour is not observed in the other houses supplied with identical heat pumps.

This is an example of how simple, electricity-only monitoring could result in better diagnostics and therefore improved performance of the heat pump system.

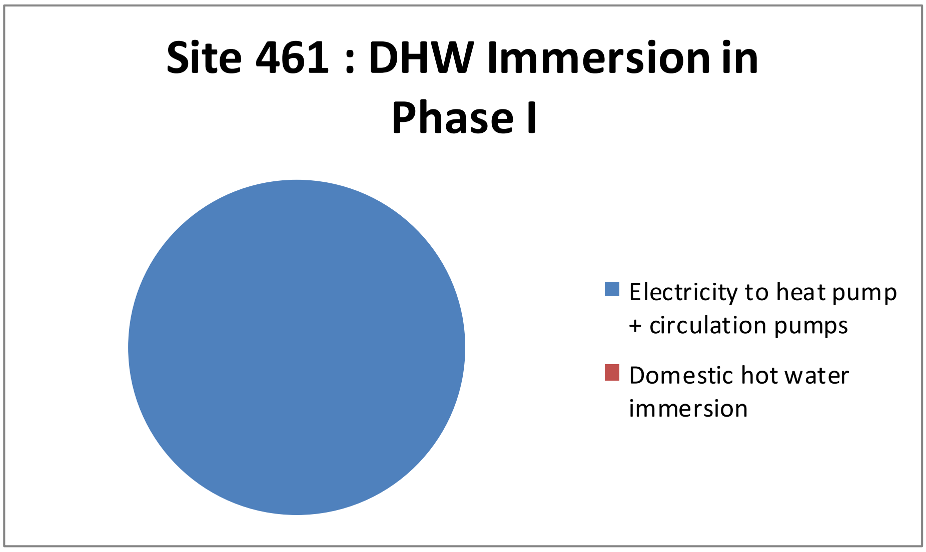


Figure 33: Electricity use by component, site 461, Phase I

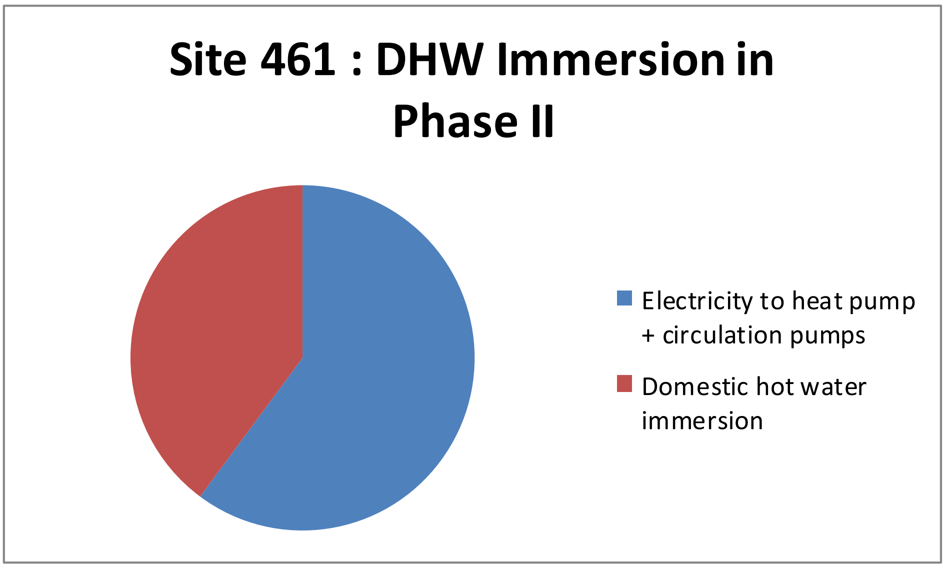


Figure 34: Electricity use by component, site 461, Phase II

4.3. Ground-source Heat Pump Supplying Radiators and Domestic Hot Water, Site 419

This ground-source heat pump extracts heat from two boreholes of 90 and 60m depth respectively and supplies radiators and domestic hot water for a three bedroomed detached house. The main house is a pre-1900 solid walled construction, with an extension added in 2004.

Heat loss calculations indicated that this heat pump (at 12 kW) was oversized and that 9.4 kW would be the optimum size according to MCS MIS 3005 Issue 3.1. However, for Phase II, the manufacturer decided to install an 8 kW heat pump, which would be undersized according to the new guidelines. The ground loop was re-filled, a 200 litre buffer tank was added and the shower was connected to the heat pump.

Figure 35 shows the schematic. The heat pump includes an auxiliary heater, which can be used both for space heating and heating of domestic hot water; in Phase II, the heat output of this auxiliary electric heater was monitored.

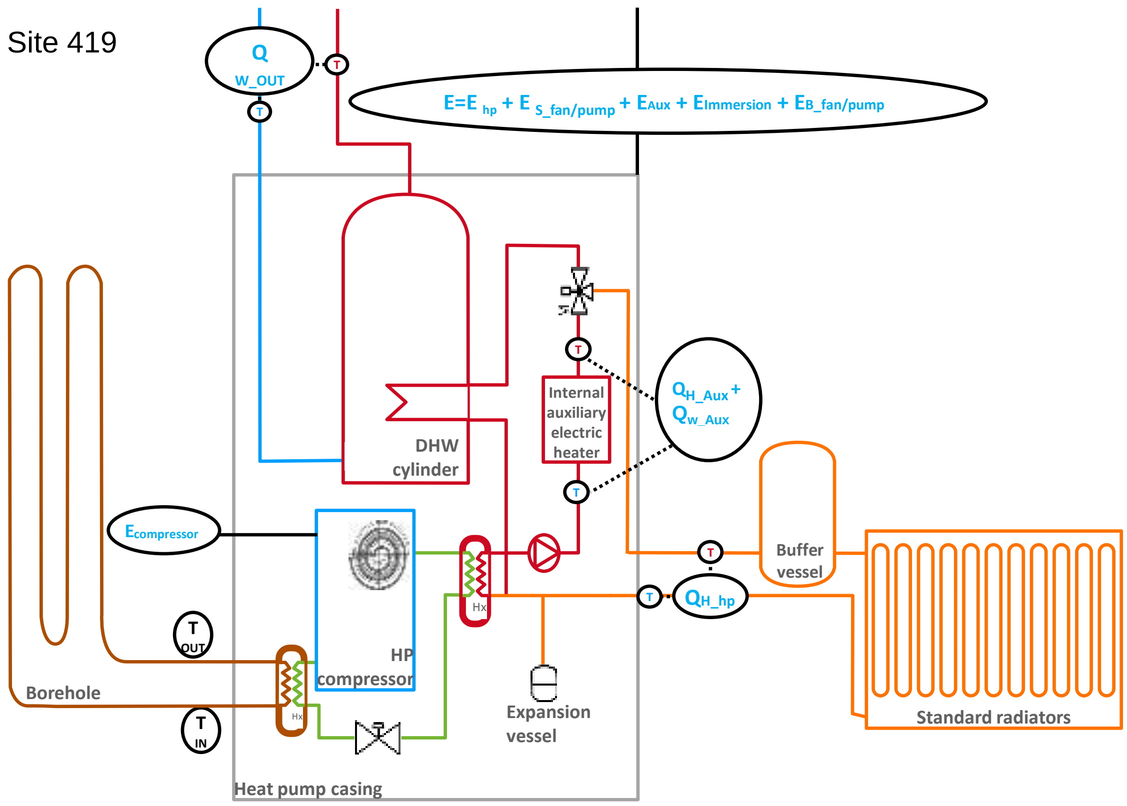


Figure 35: Schematic for site 419, Phase II

4.3.2. Calculation of SPFH1-4 and System Efficiency

In Phase II, the electricity used by the compressor was measured and was found to account for 86% of the total electricity used by the heat pump.

The remainder is used for:

- Electric auxiliary heat / domestic hot water immersion (the same for this site)
- Ground loop pump
- Circulation pump on the central heating side (variable speed DC).

Electricity consumption by the auxiliary heater has been estimated by examination of the time-series of overall electricity demand and was found to be 103 kWh. The remaining difference between the overall electricity demand of the heat pump and the electricity used by the compressor has been attributed to the ground loop pump and the circulation pumps on the central heating side, in proportion to their rated power. Table 20 shows the results.

	Compressor	Ground loop pump	Auxiliary electric heating	Circulation pumps on central heating side
Electricity demand during Phase II (kWh)	4403	(542)	(103)	(60)

Table 20: Electricity consumption by different components for site 419, Phase II

Using these assumptions, we can estimate SPF_{H1-H4}, see Table 21 and Figure 36. Estimated figures are given in brackets.

	SPF_{H1}	SPF_{H2}	SPF_{H3}	SPF_{H4}	System efficiency	Temperature corrected system efficiency
Phase I	N/A	N/A	N/A	N/A	3.04	3.03
Phase II	3.84	(3.42)	(3.37)	(3.33)	3.21	3.22

Table 21: Seasonal performance factors and system efficiency for site 419, Phase II

The system efficiency showed a small improvement from 3.04 to 3.21. The table also shows a significant difference between SPF_{H1} (3.84) and SPF_{H4} (3.33), partly due to the relatively high consumption of the ground loop pump (estimated at 540 kWh for this site).

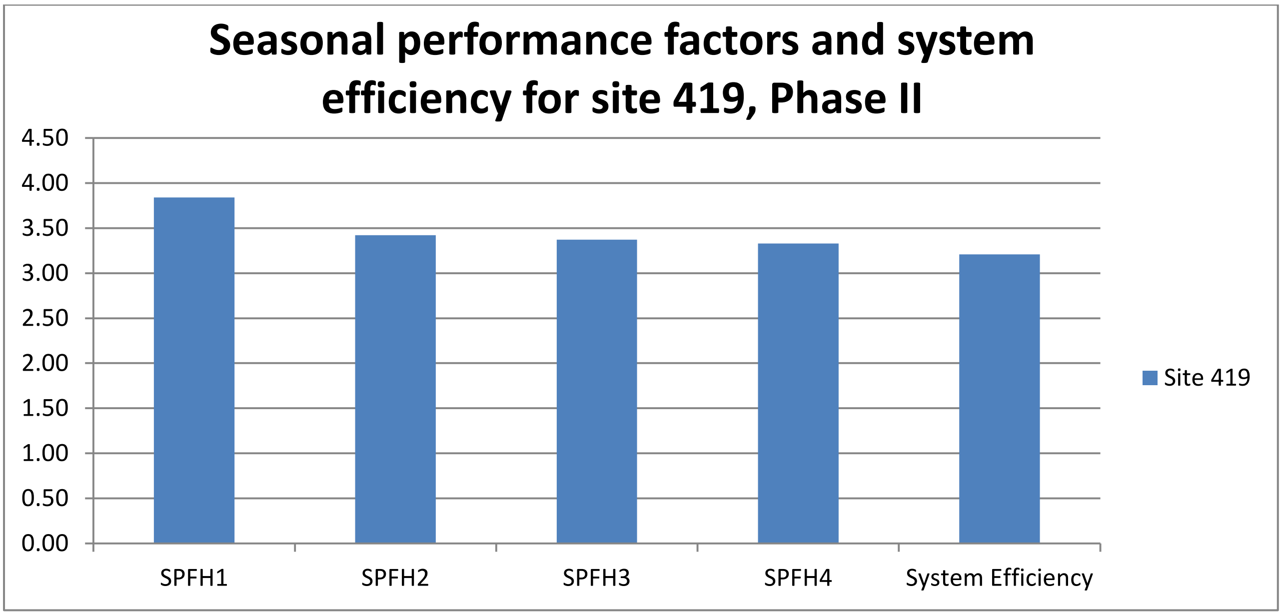


Figure 36: Seasonal performance factors and system efficiency for site 419, Phase II

It was noticeable that the amount of domestic hot water actually used by the household increased in Phase II, since the electric shower had been converted to run from the domestic hot water tank heated by the heat pump. Figure 37 shows the scatterplot of system efficiency as a function of ambient temperature; in Phase I, there is a cloud of points with very low system efficiency (between 0.5 and 1); these indicate that domestic hot water was being produced, but not used. These points are not seen in Phase II.

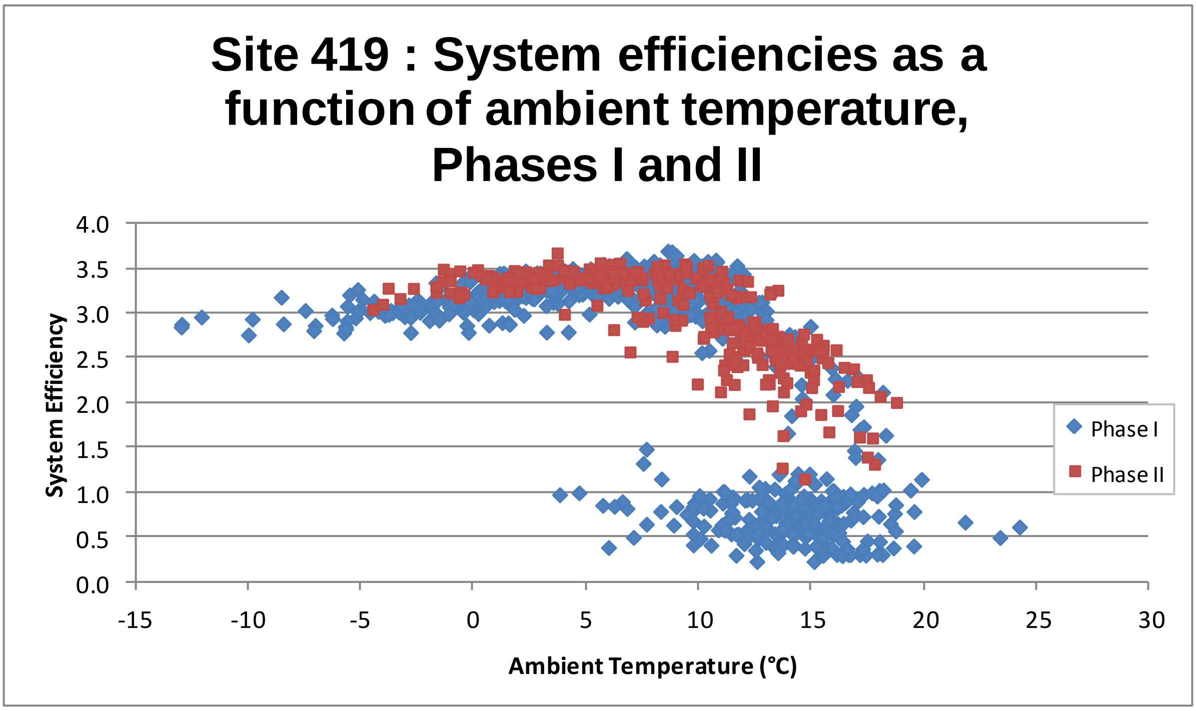


Figure 37: System efficiencies as a function of ambient temperature for site 419, Phases I & II

4.3.3. Space and Domestic Hot Water Efficiency

Detailed examination of the time series of the heat flow meters allows separate calculation of the efficiencies of space and water heating. The efficiency calculated is SPF_{H2}, i.e. the auxiliary heating and domestic hot water immersion are not included. Figure 38 shows the results.

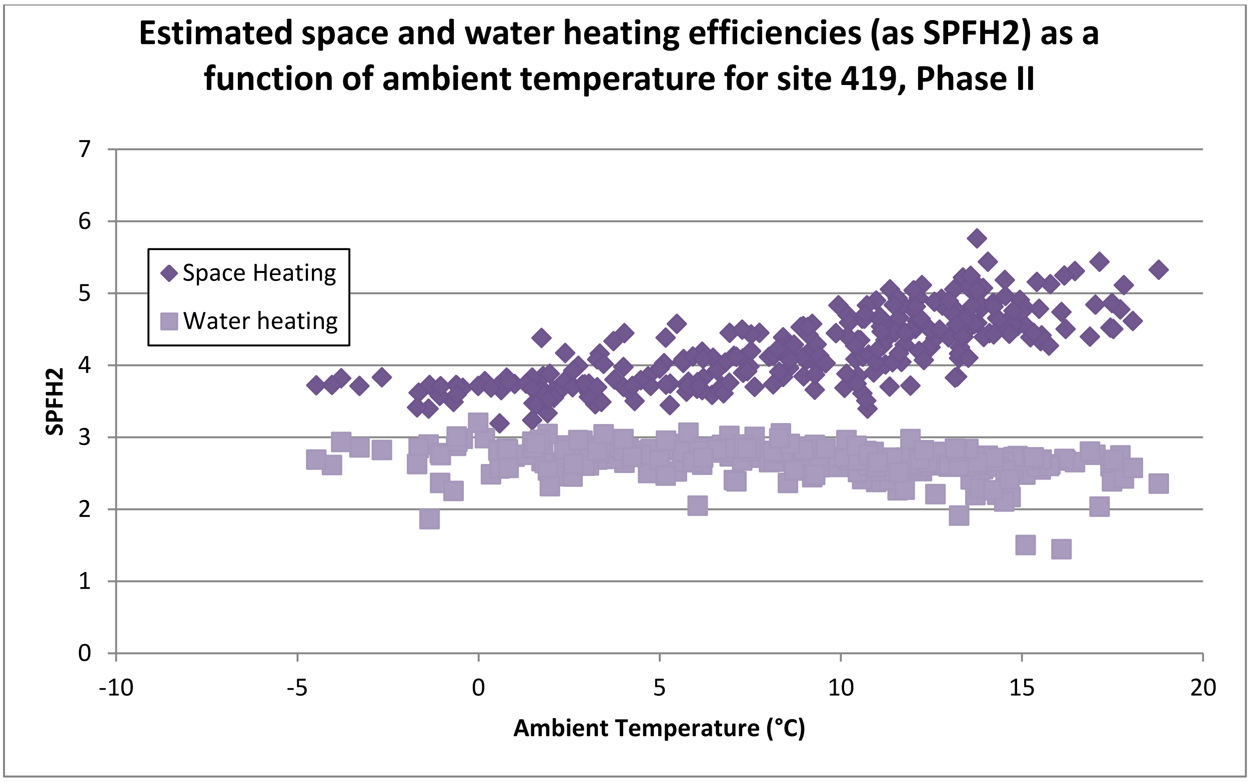


Figure 38: Estimated space and water heating efficiencies (as SPF_{H2}) as a function of ambient temperature for site 419, Phase II

Figure 38 shows space heating efficiencies of between 3.5 and 5.5, with efficiency increasing with ambient temperature, as expected for a heating system with good weather compensation. Water heating efficiency is also high, with SPF_{H2} figures falling in the range 2-3.

As mentioned in section 5.3.2, the level of electricity used for auxiliary heating for space and domestic hot water is very low at this site (estimated at 2% of the total electricity demand of the heat pump). This is an example of a heat pump with excellent performance for both space and water heating.

5. Case Studies (Medium changes)

This section presents some examples for which medium interventions were carried out between Phases I and II.

5.1. Ground-source Heat Pump Supplying Radiators and Domestic Hot Water, Site 421

This 8 kW ground-source heat pump extracts heat from a 600m ground loop and supplies radiators and domestic hot water. Figure 39 shows the schematic. The heat pump is situated in an exposed lean-to building to the side of a two bedroomed pre-1900 detached house.

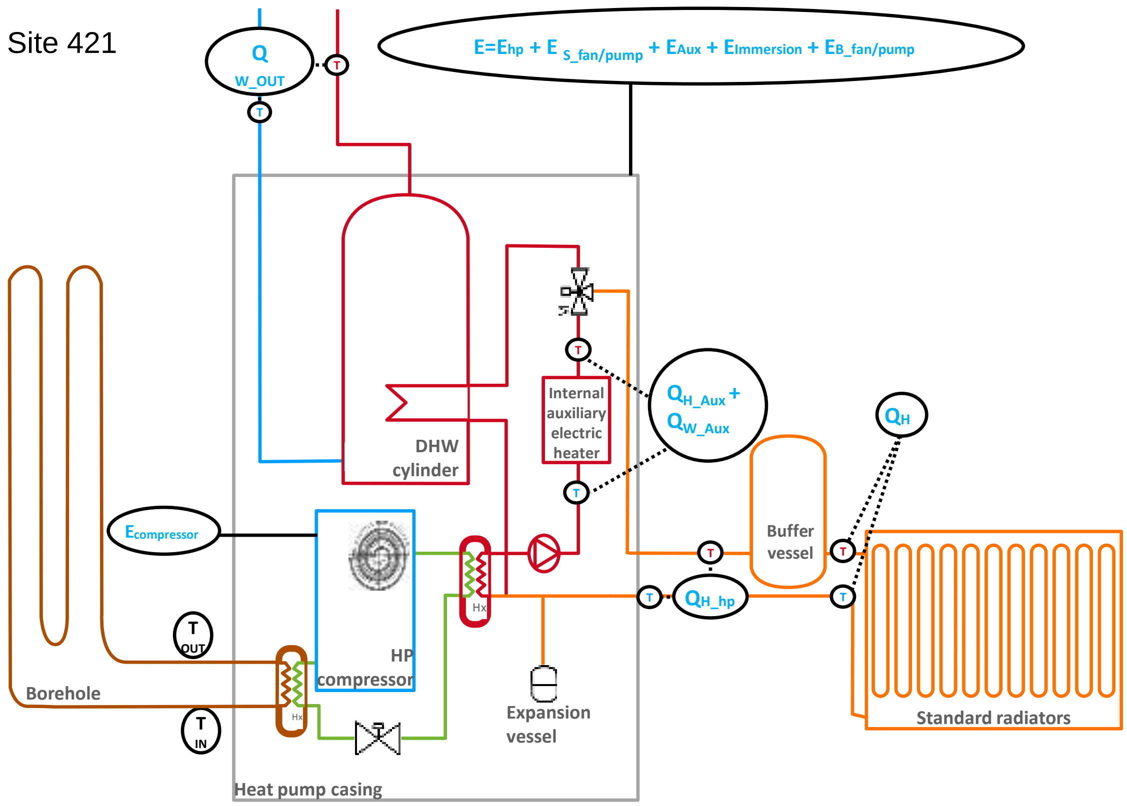


Figure 39: Schematic for site 421, Phase II

During Phase I, the auxiliary electric heater was used much of the time and engineers suspected a ground loop leak. For Phase II, the ground loop was tested and refilled, a 200 litre buffer tank was added and a variable speed DC pump fitted. The average central heating flow temperature was 39.7°C, while the average domestic hot water temperature was 45.3°C.

5.1.1. SPFH1-4 and System Efficiency

The configuration is the same as for site 419, i.e. the electricity used by the compressor was monitored in Phase II. The methodology for estimating the use of auxiliary electric heating and the electricity consumption of ground loop and central heating circulating pumps is the same as for Site 419.

Some data points were missing in the early months of Phase II and so the results presented in Table 22 refer to the period for which data availability was 100%, i.e. 01/08/2011-31/03/2012. During this period, the electricity used by the compressor was found to be 3560 kWh. Electricity consumption by other components has been estimated by inspection of the time series of electricity demand and from knowledge of the ratings of the individual components (figures in brackets below).

	Compressor	Ground loop pump	Auxiliary electric heating	Circulation pumps on central heating side
Electricity demand during Phase II 01/08/2011-31/03/2012 (kWh)	3560	(331)	(160)	(37)

Table 22: Electricity consumption by different components for site 421, Phase II

Note the very low consumption of the variable speed DC pumps on the central heating side.

As for site 419, we shall assume that the auxiliary electricity is entirely used for the production of domestic hot water. Table 23 and Figure 40 show estimated SPF_{H1-H4} and calculated system efficiency. Note that data from Phase I has been re-evaluated to correct for a faulty calibration of the electricity meter. The Phase I system efficiency has now been calculated as 2.85, instead of 1.71 as reported in reference [1].

The system efficiency appears to have improved from 2.85 in Phase I to 3.02, although it should be borne in mind that the results are not strictly comparable as the duration and ambient temperatures of the two phases were different. The scatterplot, Figure 41, shows system efficiency as a function of temperature for the two phases and confirms that a real improvement has taken place.

	Dates	SPF_{H1}	SPF_{H2}	SPF_{H3}	SPF_{H4}	System efficiency	Temperature corrected system efficiency
Phase I	01/04/2009-31/03/2010	N/A	N/A	N/A	N/A	2.85	2.84
Phase II	01/08/2011-31/03/2012	3.70	(3.38)	(3.29)	(3.26)	3.02	3.02

Table 23: Seasonal performance factors and system efficiency for site 421, Phases I & II

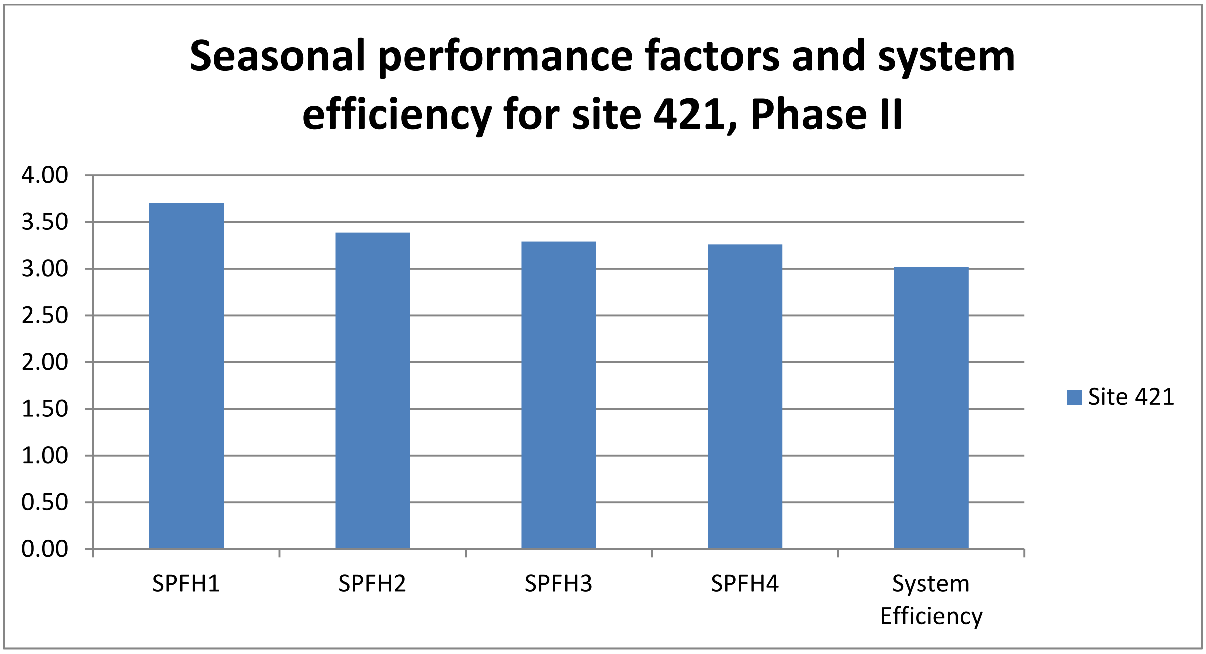


Figure 40: Seasonal performance factors and system efficiency for site 421, Phase II

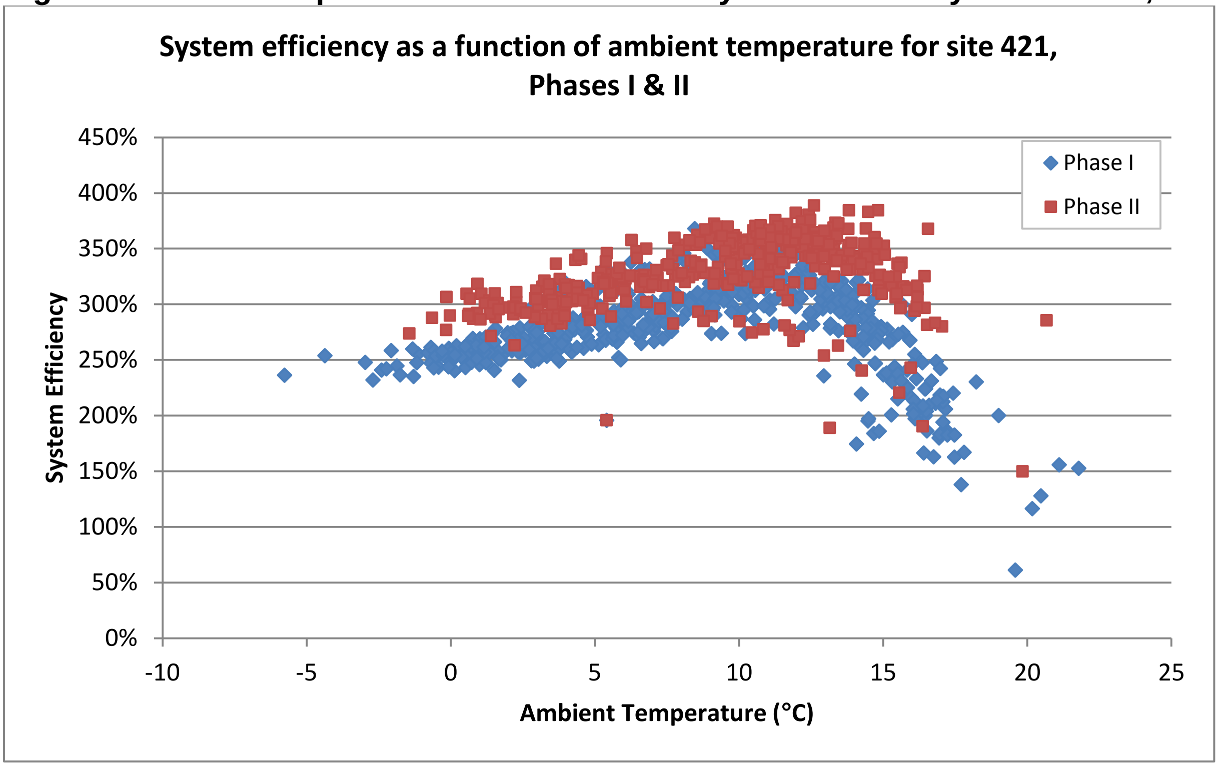


Figure 41: System efficiency as a function of ambient temperature for site 421, Phases I & II

5.1.2. Effect of refilling ground loop

During Phase I, engineers suspected a ground loop leak. This would be expected to lead to the formation of air bubbles in the glycol, thus reducing the heat transfer from the ground to the glycol. We would therefore expect the return temperature from the ground loop to be relatively low.

For this site, the ground loop was tested and refilled before the start of Phase II.

Figure 42 shows minimum daily ground return temperatures as a function of daily average ambient temperatures, for cold days (i.e. days for which the mean ambient temperature was less than 5˚C). Whilst there is considerable scatter on the chart, it can be seen that for ambient temperatures of around 0˚C, the ground return temperatures are around 1.5˚C higher in Phase II than in Phase I. This would appear to be confirmation that there was, indeed, air in the ground loop during Phase I.

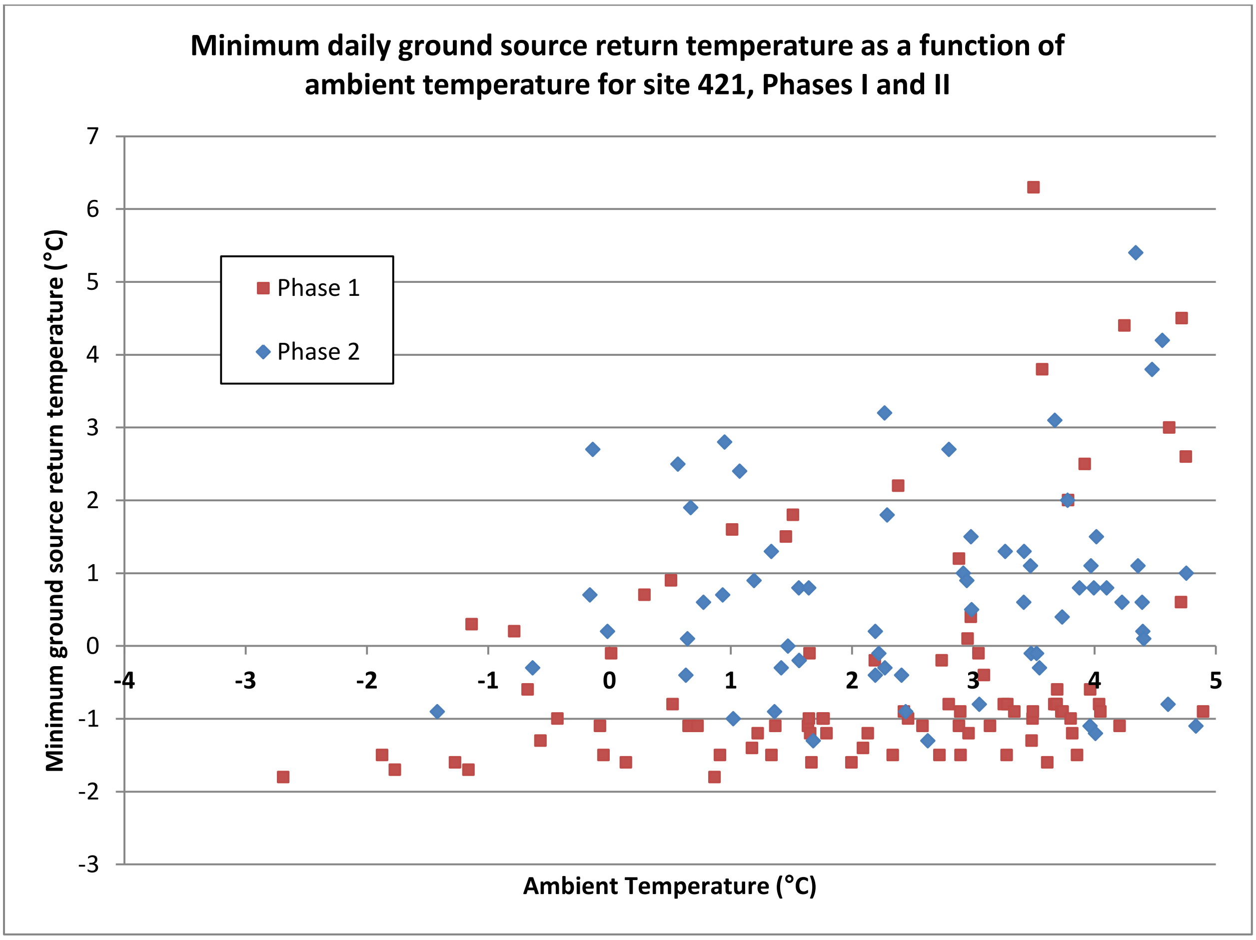


Figure 42: Minimum daily ground source return temperature as a function of ambient temperature for site 421, Phases I & II

5.2. Air-source heat pump supplying radiators and domestic hot water, site 426

Site 426 is an air-source heat pump that supplies radiators and domestic hot water for a 3 bedroomed semi-detached house. The house is of solid wall construction, with an extension built in 1998.

The most important intervention at this site was the addition of a buffer tank. The idea of installing a buffer tank is to prevent very short run times (i.e. compressor / heat pump on times). Short run times are most likely to occur during mild weather.

Other interventions at the site were the fitting of a variable speed DC pump to the central heating circuit and the repair of the room thermostat (which was identified as faulty by the service engineer).

Figure 43 shows the schematic.

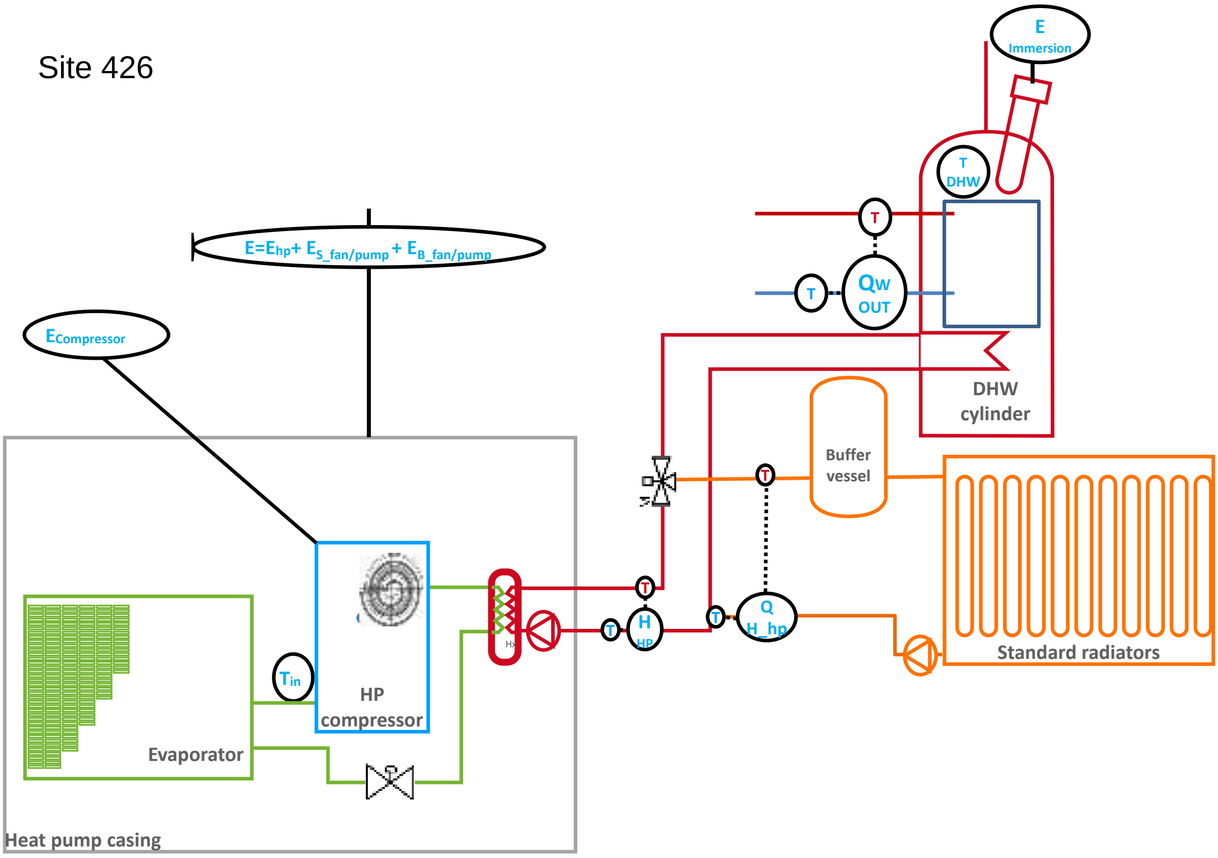


Figure 43: Schematic for site 426, Phase II

5.2.1. SPFH1-4 and System Efficiency

Table 24 shows the effect of the changes on $SPF_{H1\text{-}H4}$ and system efficiency.

	SPF_{H1}	SPF_{H2}	SPF_{H3}	SPF_{H4}	System efficiency	Temperature-corrected system efficiency
Phase I	N/A	N/A	N/A	N/A	2.61	2.33
Phase II	3.05	(2.84)	(2.60)	2.56	2.53	2.60

Table 24: Seasonal performance factors and system efficiency for site 421, Phases I & II

The temperature-corrected system efficiency has improved by 0.27 from Phase I to Phase II.

5.2.2. Effect of adding a Buffer Tank

Figure 44 shows a scatterplot of daily SPF_{H3} against daily ambient temperature (T_o) shows similar behaviour at low T_o, but some separation of the Phase I and II points at higher ambient temperatures. Investigations were carried out to determine whether this improvement in performance could be due to the buffer tank.

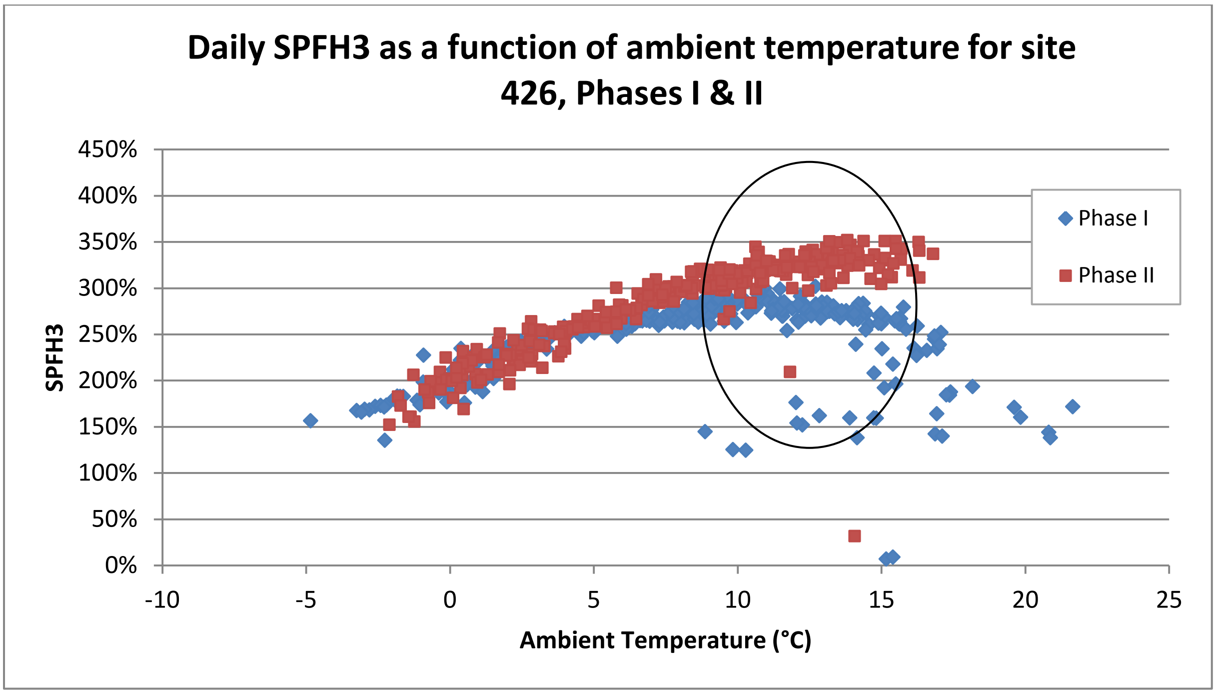


Figure 44: Daily SPF_{H3} as a function of ambient temperature for site 426, Phases I & II

The daily data totals were explored to try and identify days in Phases I and II with similar central heating energy use (CH) and average ambient temperature (T_o). No exact matches were found, with the Phase II results tending to have a slightly lower daily central heating use for the same average ambient temperature.

Figure 45 - Figure 48 show single day heat pump temperature graphs for two days in each phase. In all cases, the number of cycles per hour is similar (around 1) and a detailed look at the data suggests run times of 15 to 20 minutes in most cases.

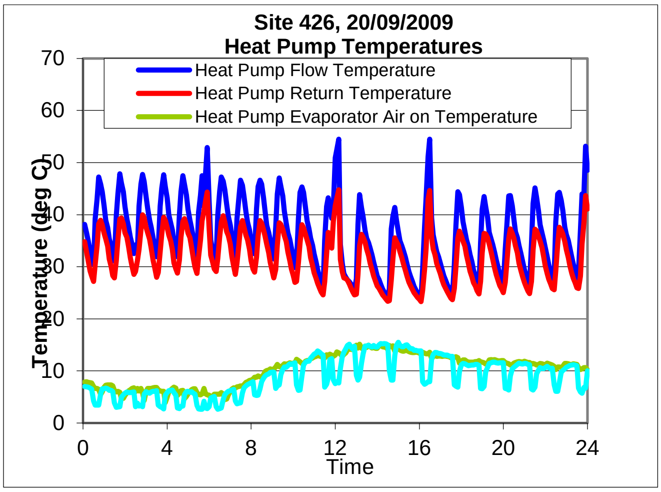


Figure 45: Heat pump temperatures on 20/09/2009 at site 426 (Phase I)
CH = 42.5 kWh, T_o = 10.4°C
SPF_{H2}=3.0, SPF_{H4}=2.6

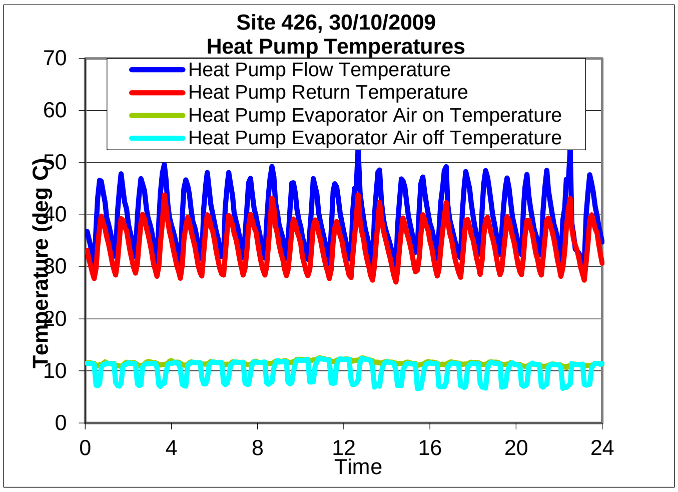


Figure 46: Heat pump temperatures on 30/10/2009 at site 426 (Phase I)
CH = 61.5 kWh, T_o = 11.5°C
SPF_{H2}=3.2, SPF_{H4}=2.9

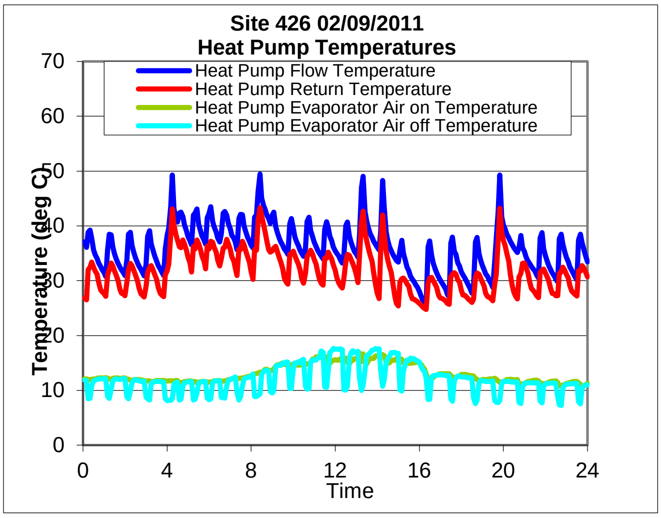


Figure 47: Heat pump temperatures on 02/09/2011 at site 426 (Phase II)
CH = 44.7 kWh, T_o = 13.5°C
SPF_{H2}=3.6, SPF_{H4}=3.4

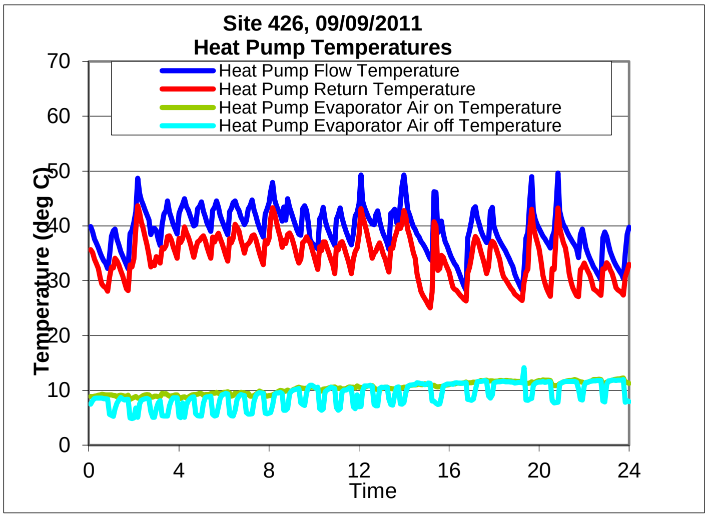


Figure 48: Heat pump temperatures on 09/09/2011 at site 426 (Phase II)
CH = 57.5 kWh, T_o = 10.9°C
SPF_{H2}=3.3, SPF_{H4}=3.2

The only really striking difference between the Phase I and Phase II graphs is the way the flow temperature varies across the day. In all cases there are a few spikes in flow temperature corresponding to domestic hot water heating; but, other than these spikes, the Phase I data shows both more consistent and higher peaks in flow temperature during each cycle. The Phase II results show very clear periods of reduced flow temperatures and, even during periods of raised flow temperatures, cycle peaks generally appear lower than during Phase I, although the number of peaks per day is similar in both phases. The corresponding electricity demand is shown in Figure 49 - Figure 52, below.

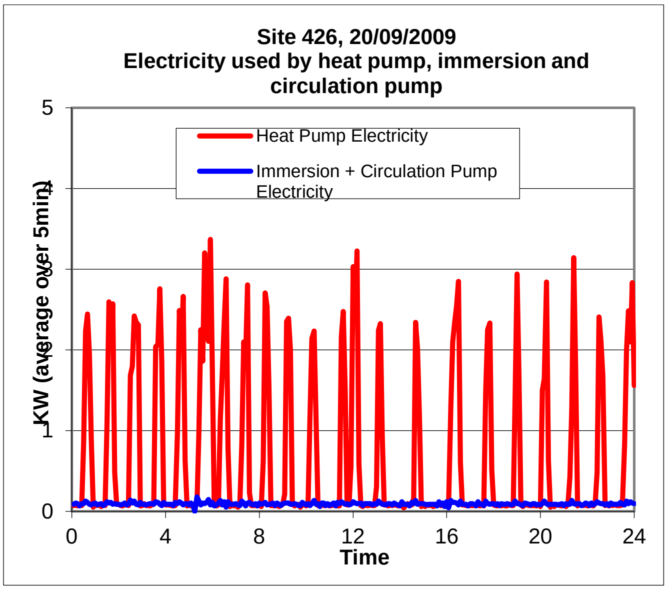


Figure 49: Electricity consumption, site 426, 20/09/2009 (Phase I)
CH = 42.5 kWh, T_o = 10.4°C
SPF_{H2}=3.0, SPF_{H4}=2.6

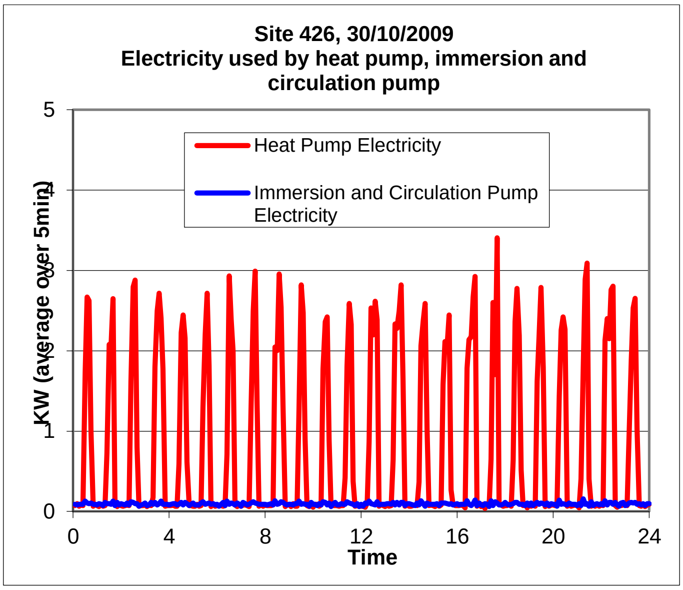


Figure 50: Electricity consumption, site 426, 30/10/2009 (Phase I)
CH = 61.5 kWh, T_o = 11.5°C
SPF_{H2}=3.2, SPF_{H4}=2.9

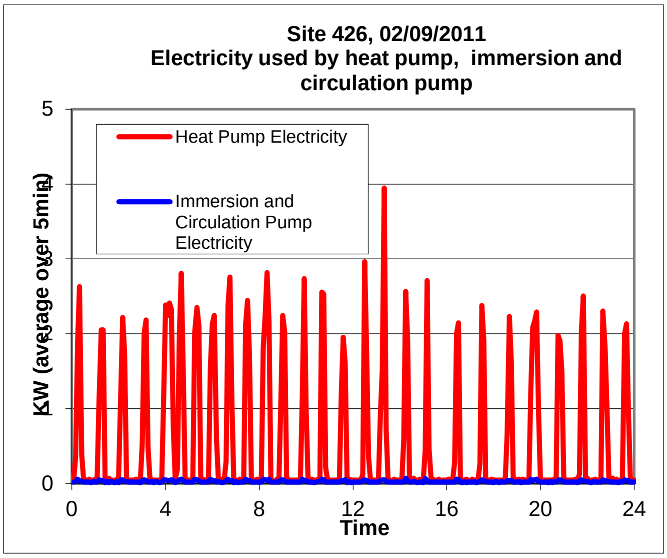


Figure 51: Electricity consumption, site 426, 02/09/2011, Phase II
CH = 44.7 kWh, T_o = 13.5°C
SPF_{H2}=3.6, SPF_{H4}=3.4

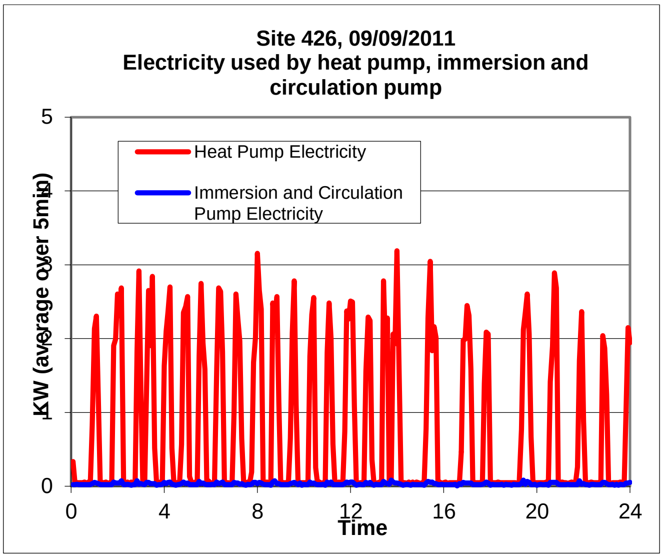


Figure 52: Electricity consumption, site 426, 09/09/2011, Phase II
CH = 57.5 kWh, T_o = 10.9°C
SPF_{H2}=3.3, SPF_{H4}=3.2

The blue lines represent the power drawn by the indoor unit which houses both the domestic hot water tank and the circulation pump. In the Phase I examples, there is a continuous, low level of power consumption – due to the circulation pump. In the Phase II examples, this power consumption is lower (due to the installation of a high efficiency DC pump) and cycles very close to zero (see expanded view in Figure 53). Circulation pumps switch to a very low level when there is no demand for heat, – i.e. the room thermostat is satisfied.

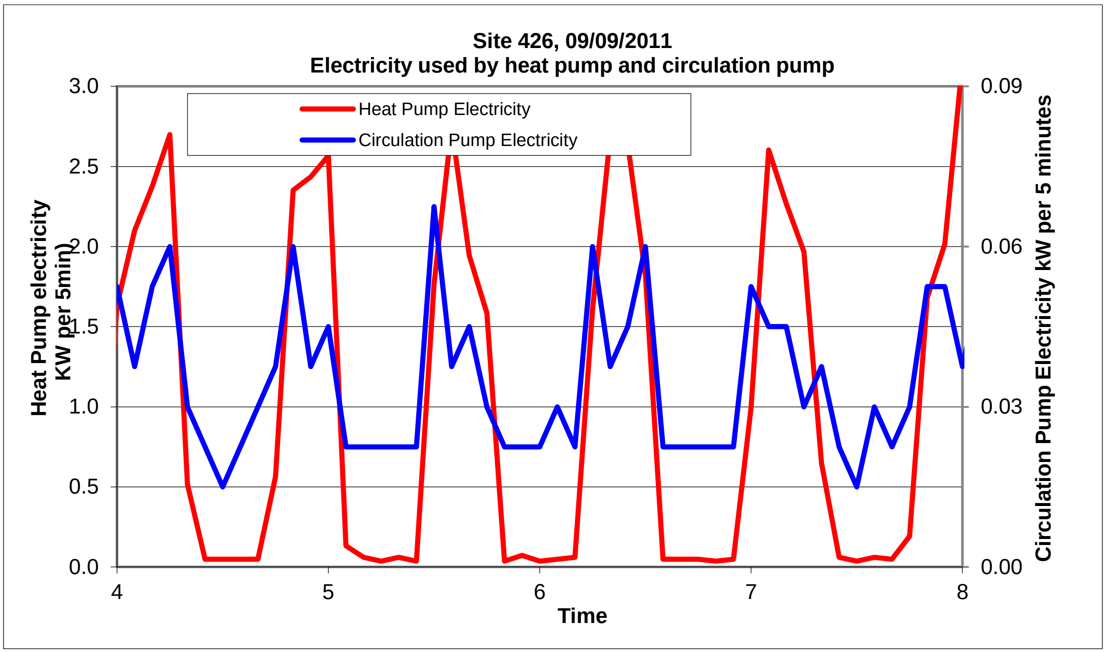


Figure 53: Electricity consumption of the heat pump and circulation pump at site 426 during a mild day in Phase II

Thus we can deduce that the change in behaviour in Phase II during these mild weather conditions is due to the system cycling off on thermostat setting, whereas it cycled off on the return temperature at the heat pump during Phase I. Hence the low peaks in flow temperature (and hence the improved SPF_{H3}) are due to the room thermostat switching the heat pump off before the heat pump has reached its own internal return temperature set-point.

An alternative explanation for the reduced flow and return temperatures seen during Phase II is that the results seem to indicate that a set-back thermostat is in operation – overnight and late afternoon / evening - although there is no conclusive evidence for this in the room temperatures (not shown here), which remain fairly flat at around 22°C throughout each of these Phase II days.

The buffer tank is likely to slow the response of the heat pump, which may, in turn, make it more likely that the heat pump will cycle on room thermostat, but it appears that the main contributor to the improved SPF_{H3} during Phase II is the improved thermostat behaviour.

5.3. Ground-source heat pump supplying underfloor heating and domestic hot water, Site 416

This ground source heat pump extracts heat from a 300m ground loop and supplies underfloor heating and domestic hot water for a highly efficient 4 bedroomed detached house built in 2008. Figure 54 shows the schematic.

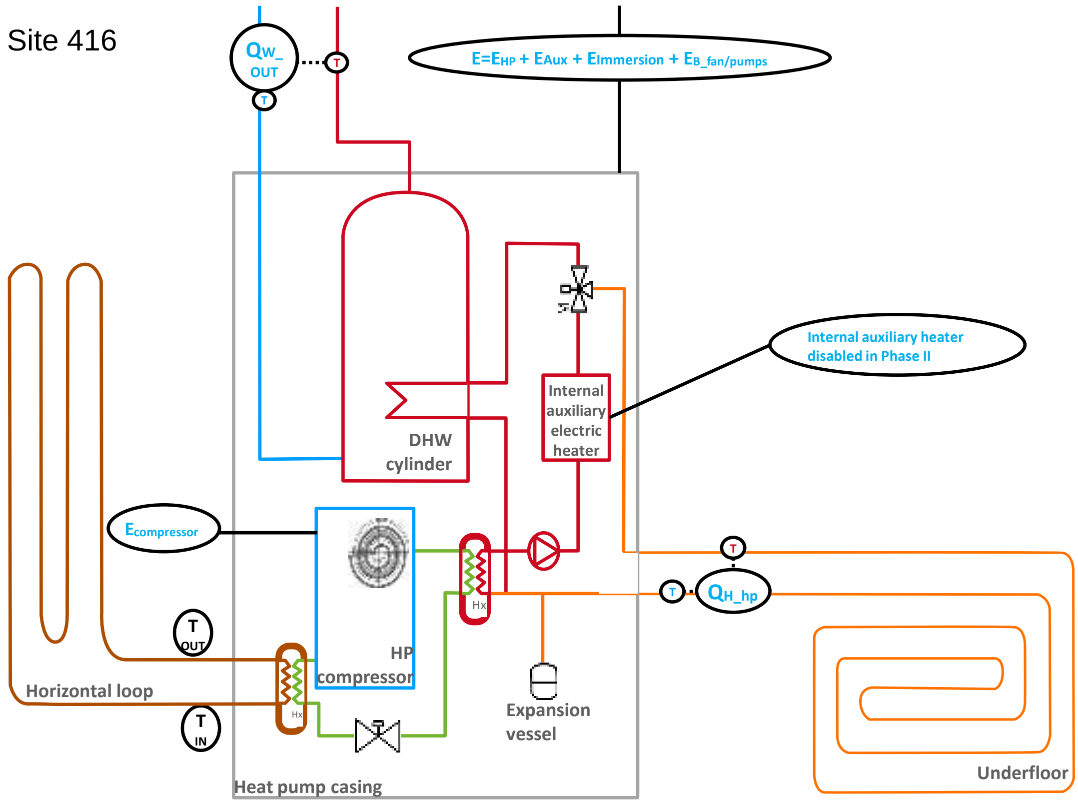


Figure 54: Schematic for site 416, Phase II

5.3.1. SPFH1-4 and System Efficiency

During phase I, excessive use of the auxiliary heating resulted in poor overall efficiency. For Phase II, only two modifications were made at this site; **the auxiliary heating was disabled** and the circulation pump was replaced by a variable speed DC pump. Table 25 shows the system efficiencies for Phases I and II and SPF_{H1-H4} for Phase II.

	SPF_{H1}	SPF_{H2}	SPF_{H3}	SPF_{H4}	System efficiency	Temperature corrected system efficiency
Phase I	N/A	N/A	N/A	N/A	2.35	2.31
Phase II	4.41	(3.94)	(3.94)	3.89	3.28	3.29

Table 25: Seasonal performance factors and system efficiency for site 416, Phases I & II

The resulting temperature-corrected system efficiency has improved from 2.31 to 3.29. This example demonstrates very clearly the importance of controlling the use of auxiliary electric heating. **An important corollary of this finding is that controls must clearly indicate to the**

householders whether auxiliary electric heating is enabled or not; the controls should not simply be labelled "summer setting" or "winter setting".

5.3.2. Central heating flow and return temperatures

Figure 55 shows the flow and return temperatures for the central heating system. It can be seen that the flow temperatures are very low (between 30 and 35˚C throughout the heating season). This explains the excellent efficiency.

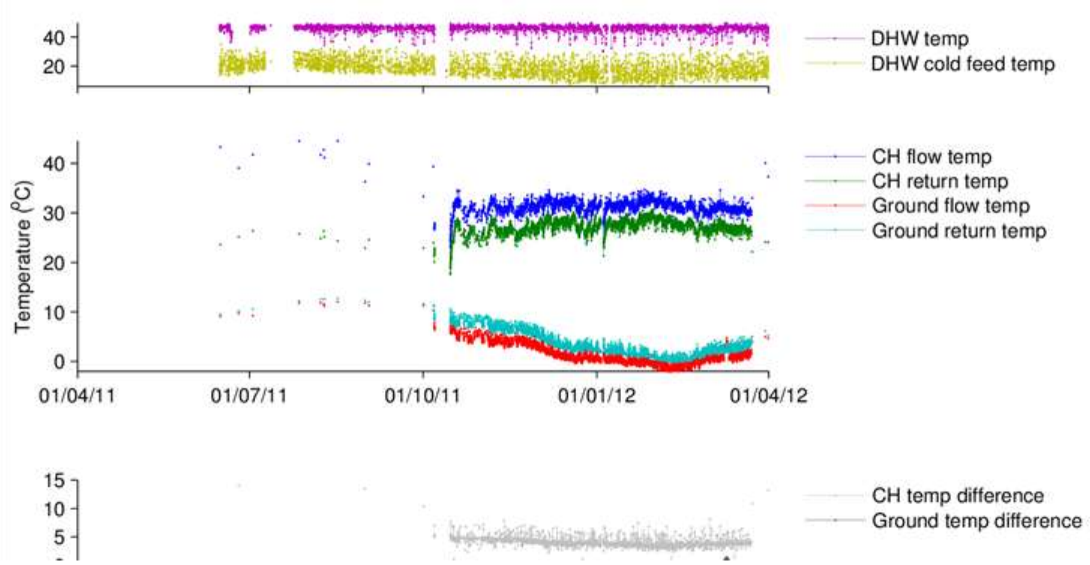


Figure 55: Central heating, domestic hot water and ground flow and return temperatures, site 416

5.4. Ground-source heat pump supplying radiators and domestic hot water, Site 437

This ground-source heat pump extracts heat from a borehole and supplies radiators and domestic hot water for a three bedroomed semi-detached house.

Site 437

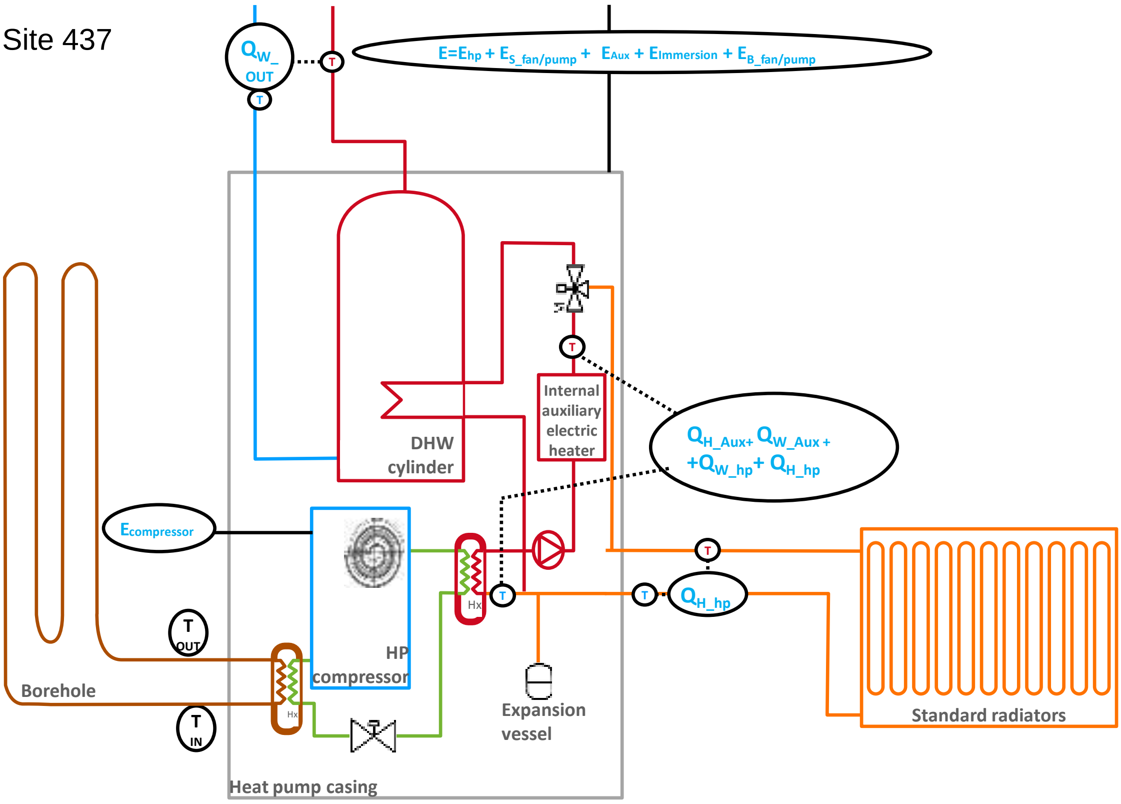


Figure 56 shows the schematic.

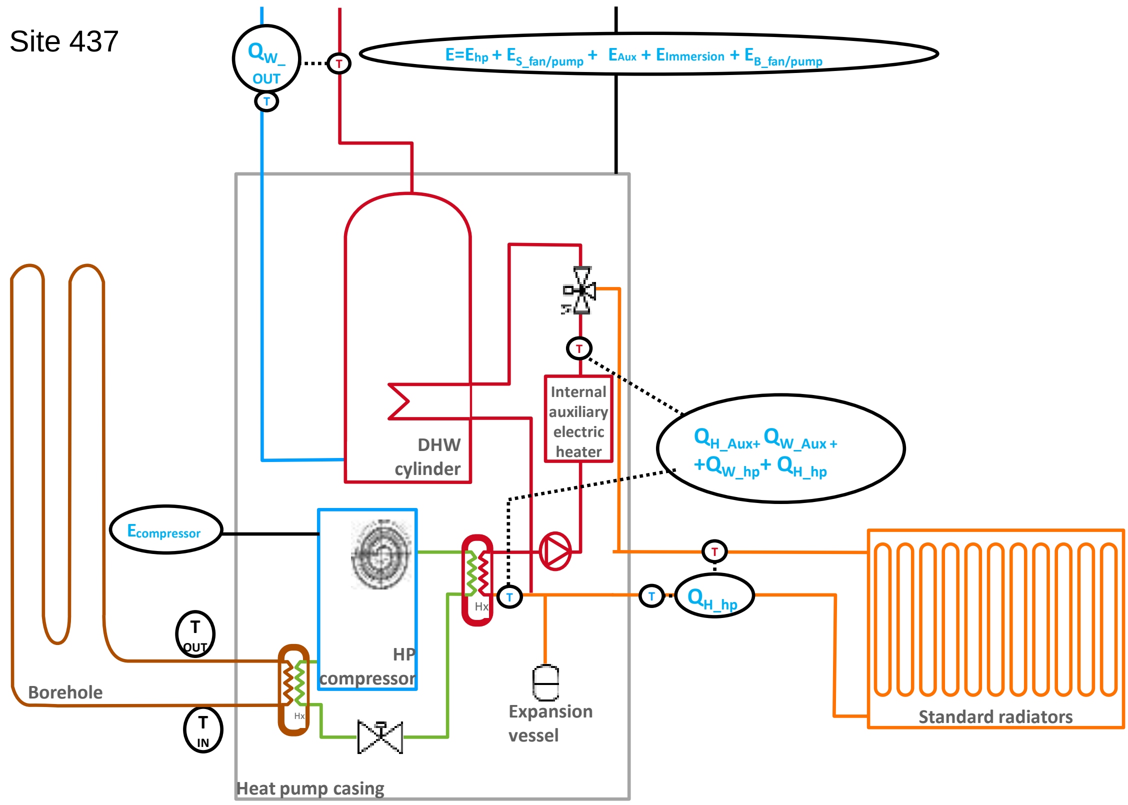


Figure 56: Schematic for site 437, Phase II

During Phase I, excessive use of the auxiliary electric heating resulted in poor overall efficiency. The bypass valve was faulty, which meant that the central heating was sometimes on even in summer. During the winter, some very low ground loop return temperatures were recorded (around -3°C).

For Phase II, a number of changes were made:

- voltage optimiser installed[12]
- extensive changes to control parameters. The degree of weather compensation was reduced, as was the sensitivity to the room thermostat. The summer disconnect temperature was also reduced. Finally, the storage temperature of the domestic hot water was reduced to 46°C, with a weekly pasteurisation cycle.
- variable speed central heating pumps installed
- bypass valve closed.

Note that the configuration is similar to that for site 416, except that the internal auxiliary heater was not disabled in Phase II.

[12] See section 1.2 for a summary of the likely effects of voltage optimisers on heat pump performance.

5.4.1. SPFH1-4 and system efficiency

Table 26 shows estimated electricity consumption by each component, calculated as per the methodology for site 419. Estimated figures are in brackets.

	Compressor	Ground loop pump	Auxiliary heater	Circulation pumps on central heating side
Electricity demand during Phase II (01/05/2011-31/03/2012) (kWh)	2267	(229)	(3998)	(98)

Table 26: Electricity consumption by different components for site 437, Phase II

Table 27 and Figure 57 show the effect of the modifications on heat pump and system performance. It can be seen that, despite the modifications, the overall temperature-corrected system efficiency has fallen from 2.28 to 1.43.

	SPF_{H1}	SPF_{H2}	SPF_{H3}	SPF_{H4}	System Efficiency	Temperature corrected system efficiency
Phase I	N/A	N/A	N/A	N/A	2.28	2.28
Phase II	3.09	(2.80)	(1.69)	(1.67)	1.48	1.43

Table 27: Seasonal performance factors and system efficiency for site 437, Phase I & II

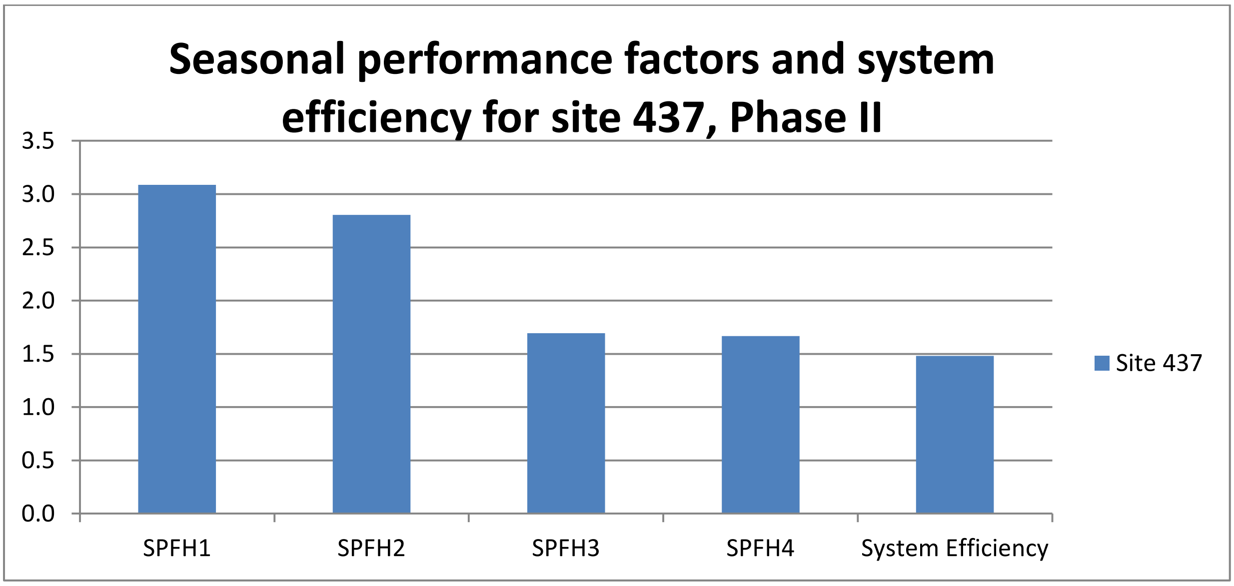


Figure 57: Seasonal performance factors and system efficiency for site 437, Phase II

The performance of the heat pump, as measured by SPF_{H2} is reasonable (2.80), although it is not clear whether this should be attributed to the control changes, the repair of the bypass valve, the installation of the voltage optimiser, or all three. It is suggested that laboratory tests are carried out to establish whether use of a voltage optimiser can produce significant savings.

The heat pump developed a fault in December, after which the auxiliary electric heating was used extensively, which accounts for the low SPF_{H3}, SPF_{H4} and system efficiency.

5.4.2. Auxiliary electricity consumption

Figure 58 shows the time series of auxiliary electricity consumption by the heat pump; for most of the monitoring period, the auxiliary heating is used only for the weekly sterilisation cycle; after the fault developed in December 2011, the auxiliary heater provided all the heat, until the heat pump was fixed in February 2012.

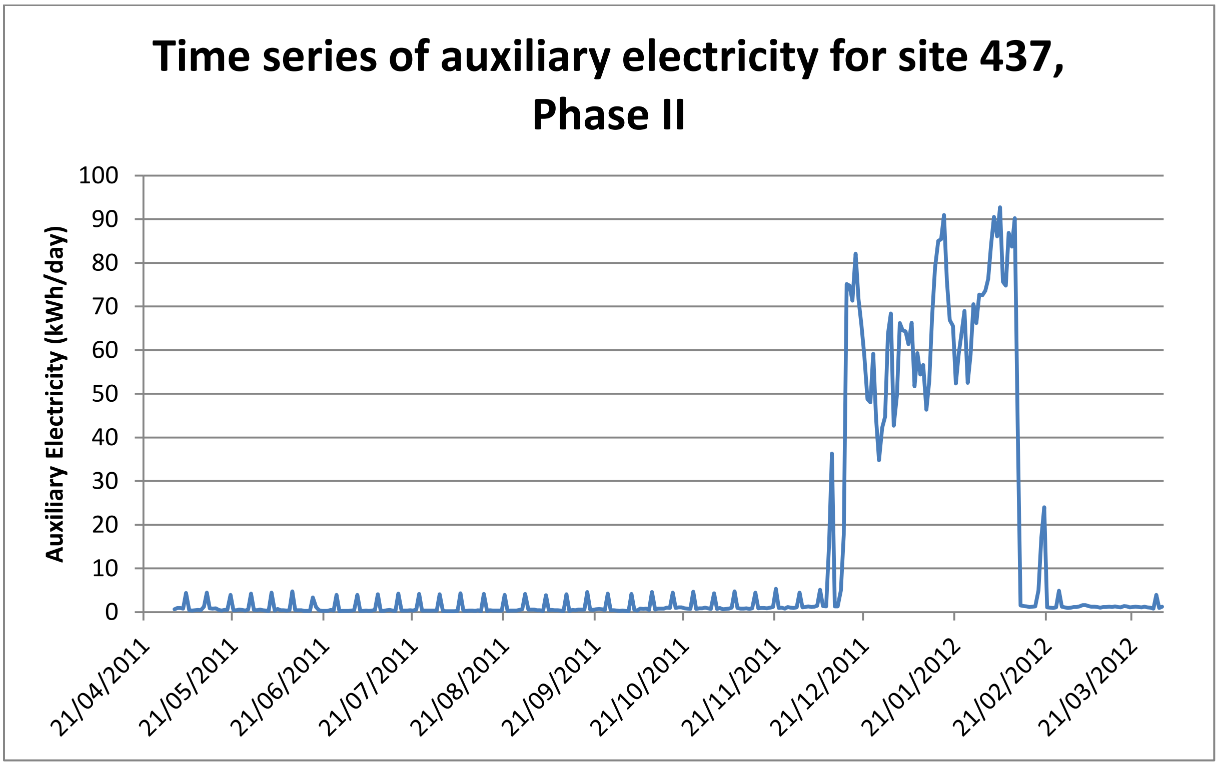


Figure 58: Time series of auxiliary electricity consumption for site 437, Phase II

The time series of electricity demand shows the period of failure (14/12/2011- 25/02/2012), i.e. 73 days. Excluding the period for which the system was faulty, the average SPF_{H4} was 2.70, indicating good performance for this site. The estimated effect of the failure was to increase the householders' bill by around £350.

This example underlines the necessity of diagnostics to inform the householder that the heat pump is not working. Remote sensing could also be a useful way to avoid such errors.

5.5. Ground-source heat pump supplying radiators and domestic hot water, Site 432

This house is a one bedroomed semi-detached bungalow. A 4 kW ground source heat pump extracts heat from a vertical panel and supplies heat to radiators and domestic hot water. The vertical panel can be recharged by solar thermal panels in the summer. Figure 59 shows the schematic.

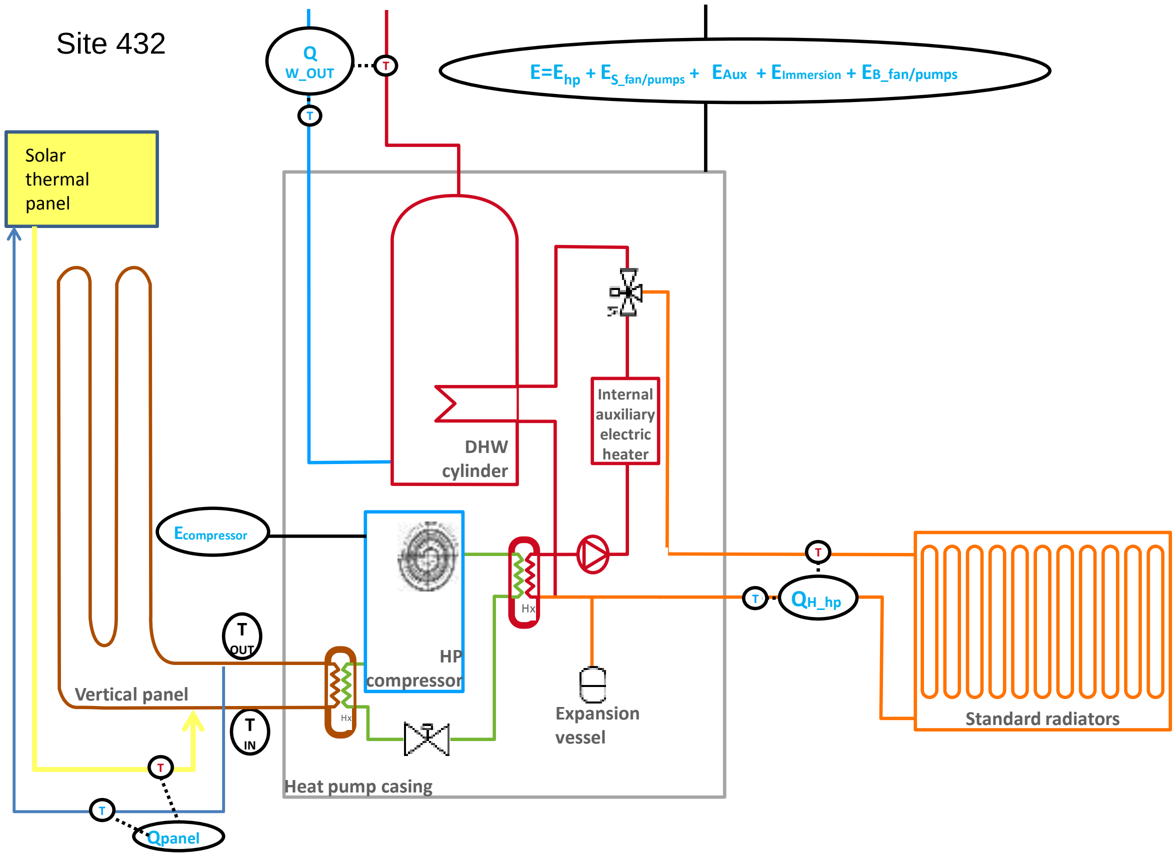


Figure 59: Schematic for site 432, Phase II

A range of interventions were carried out at this site including:

- disabling one of the circulation pumps on the central heating circuit
- reducing the temperature of the domestic hot water to 46°C with a weekly sterilisation pattern
- making comprehensive changes in control parameters, notably an increase in the delay before the auxiliary heaters are engaged (now 90 minutes)
- altering the parameters for weather compensation.

5.5.1. SPFH1-4 and System Efficiency

Table 28 shows the electricity consumption by component. The electricity consumed by the compressor has been measured separately at this site; auxiliary heating has been estimated by inspection of the time series. The procedure for estimating the electricity consumption by the ground loop pump and central heating pumps is as for site 419. Estimated figures are in brackets.

	Compressor	Ground loop pump	Auxiliary heating	Circulation pump on central heating side
Electricity consumption during Phase II (kWh)	1896	(421)	(163)	(181)

Table 28: Electricity consumption by different components for site 432, Phase II

Table 29 and Figure 60 show a clear improvement in both SPF_{H4} and system efficiency during Phase II as compared to Phase I. This is due to lower use of the auxiliary heating, as discussed in section 6.5. The circulation pump on the central heating side is internal to the heat pump; further improvements in SPF could probably be achieved by using lower energy pumps.

	SPF_{H1}	SPF_{H2}	SPF_{H3}	SPF_{H4}	System efficiency	Temperature corrected system efficiency
Phase I	N/A	N/A	N/A	(2.26)	1.82	1.80
Phase II	3.59	(2.94)	(2.81)	(2.64)	2.28	2.35

Table 29: Seasonal performance factors and system efficiency for site 432, Phases I & II

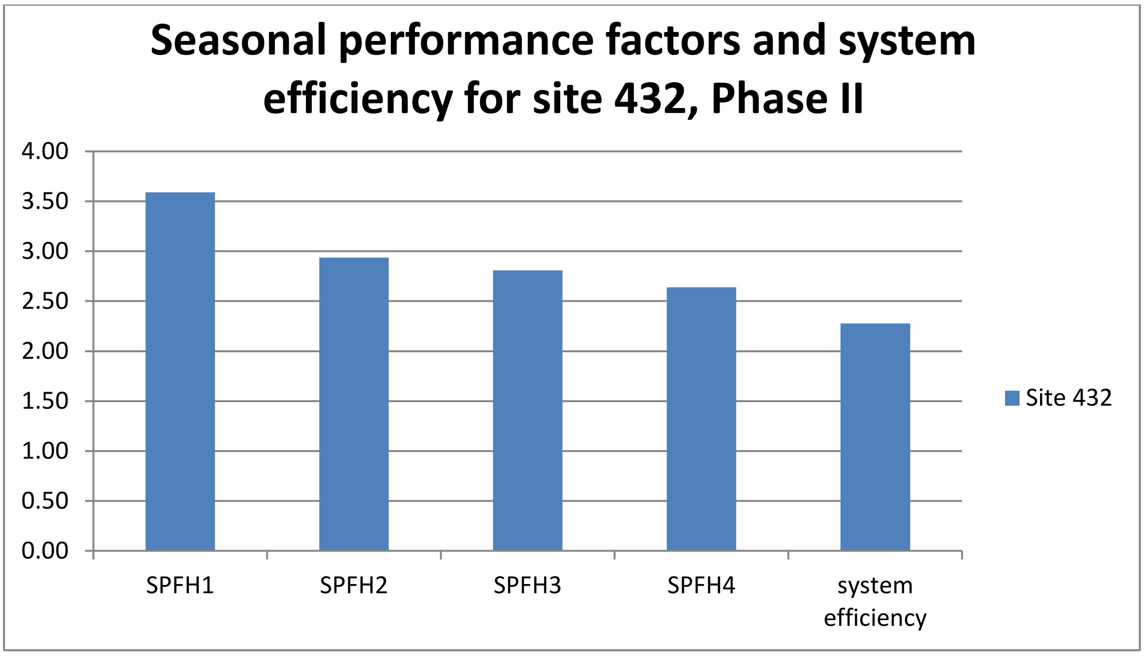


Figure 60: Seasonal performance factors and system efficiency for site 432, Phase II

5.5.2. Use of domestic hot water immersion

In this site, a single auxiliary electric heater can provide supplementary heat for either space heating or domestic hot water. During the first phase of the trial, the low SPF_{H4} was attributed to over-use of the auxiliary electric heater. The control parameters were changed to ensure that the supplementary space heating did not come on at the expense of the heat pump.

Figure 61 shows a time series of total electricity demand minus the compressor electricity during the second phase of the trials. The weekly sterilisation pattern is apparent and accounts for almost all of the consumption of the auxiliary heater.

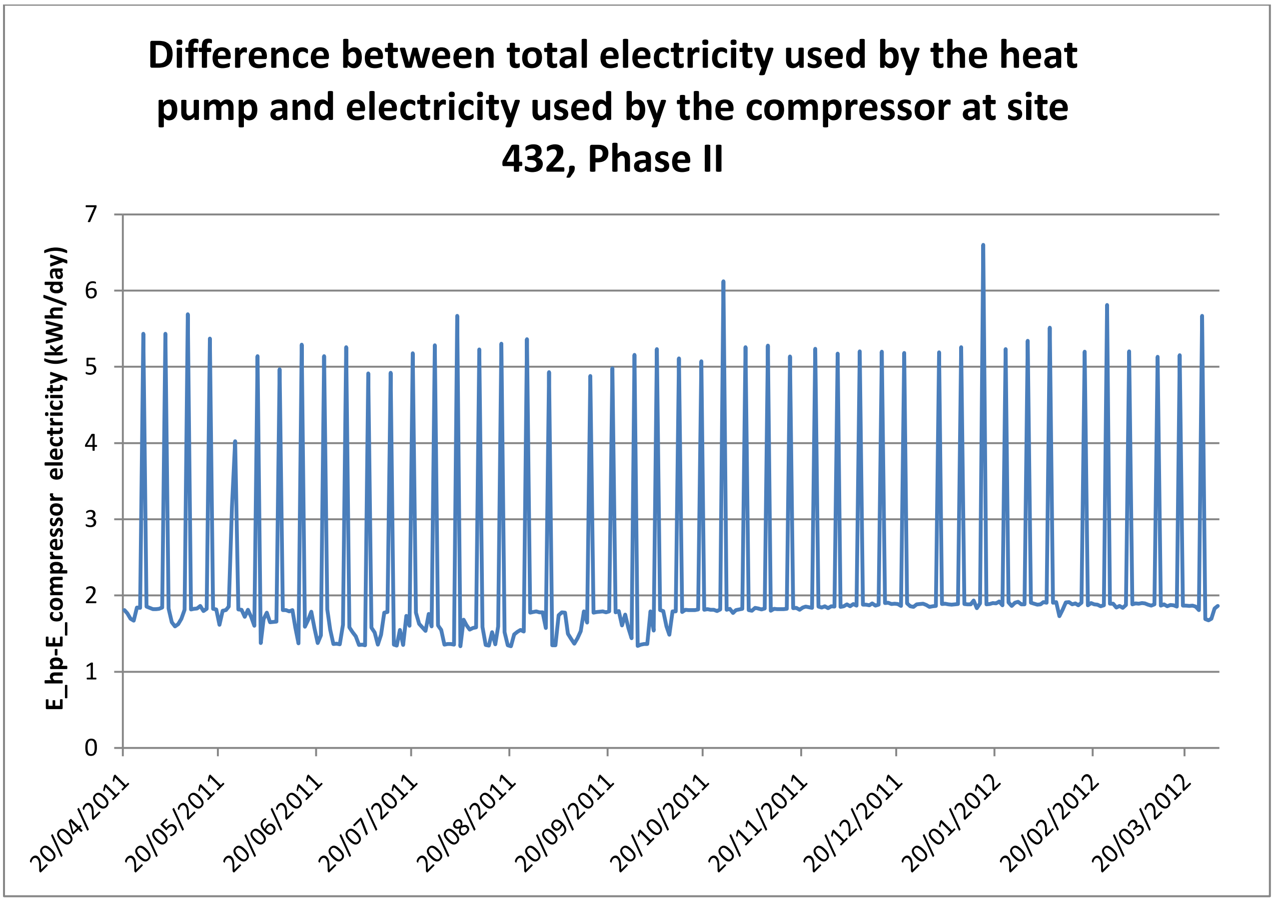


Figure 61: Difference between total electricity used by the heat pump and electricity used by the compressor at site 432, Phase II

Figure 62 shows a scatterplot of space heating efficiency and water heating efficiency with days on which the sterilisation cycle is undertaken shown separately.

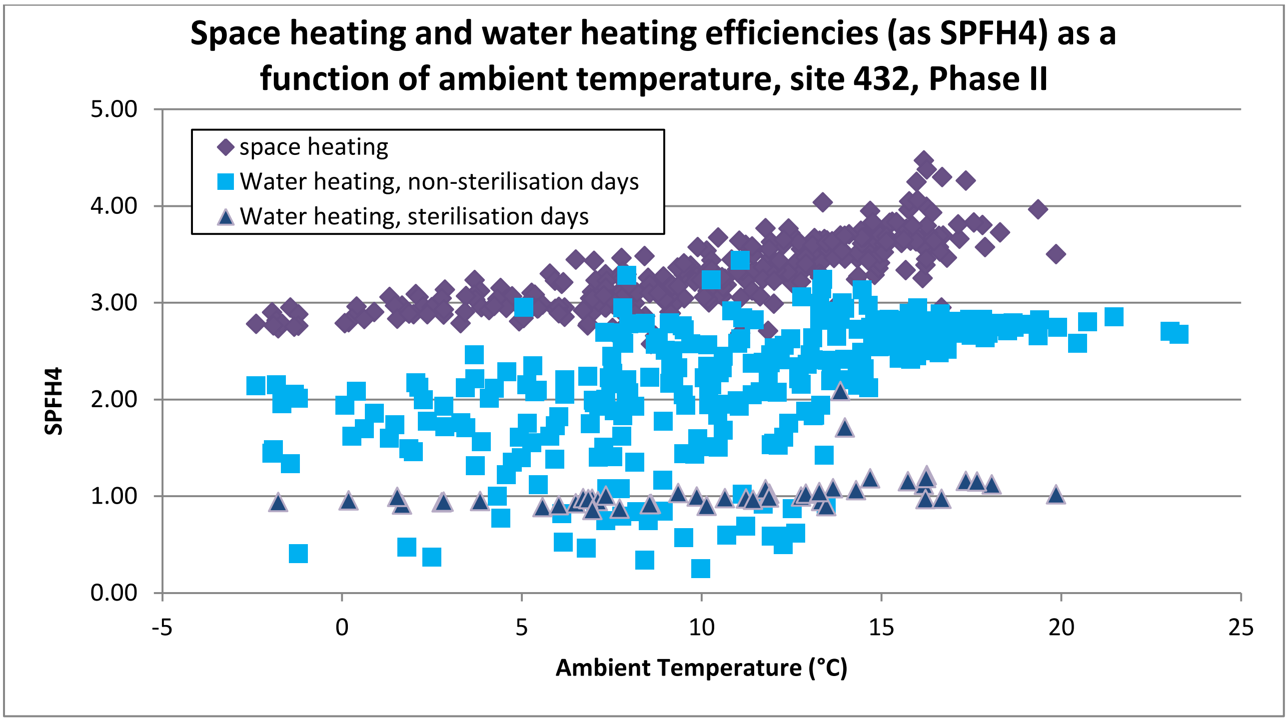


Figure 62: Space and water heating efficiencies (as SPF_{H4}) as a function of ambient temperature, showing effect of sterilisation, site 432, Phase II

The scatterplot of overall daily SPF_{H4} (for both space and water heating) as a function of ambient temperature shows the effect of the weekly sterilisation on performance (Figure 63). It should be stressed that this site is well configured and operates efficiently; the figure does not indicate any fault, but it does indicate that there could be merit in investigating alternative means of control of Legionella and other bacteria.

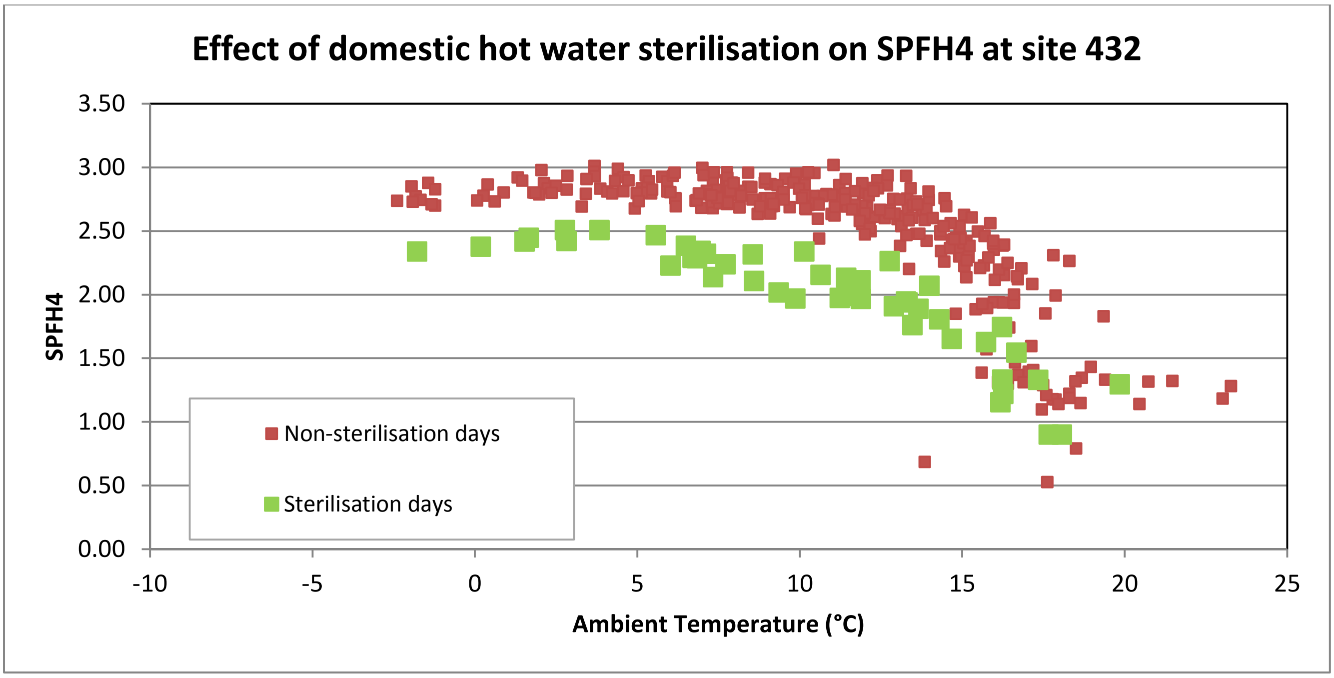


Figure 63: Effect of domestic hot water sterilisation on SPF_{H4} at site 432

5.6. Ground-source Heat Pump Supplying Radiators and Domestic Hot Water, Site 460

At this site, a 3.5 kW ground-source heat pump supplies radiators and domestic hot water for a semi-detached bungalow. The schematic is shown in Figure 64. During Phase I, the flap valve that diverts heat between the domestic hot water and central heating circuits became faulty. This was repaired for phase II, but the problem re-occurred in June 2011 and was fixed again.

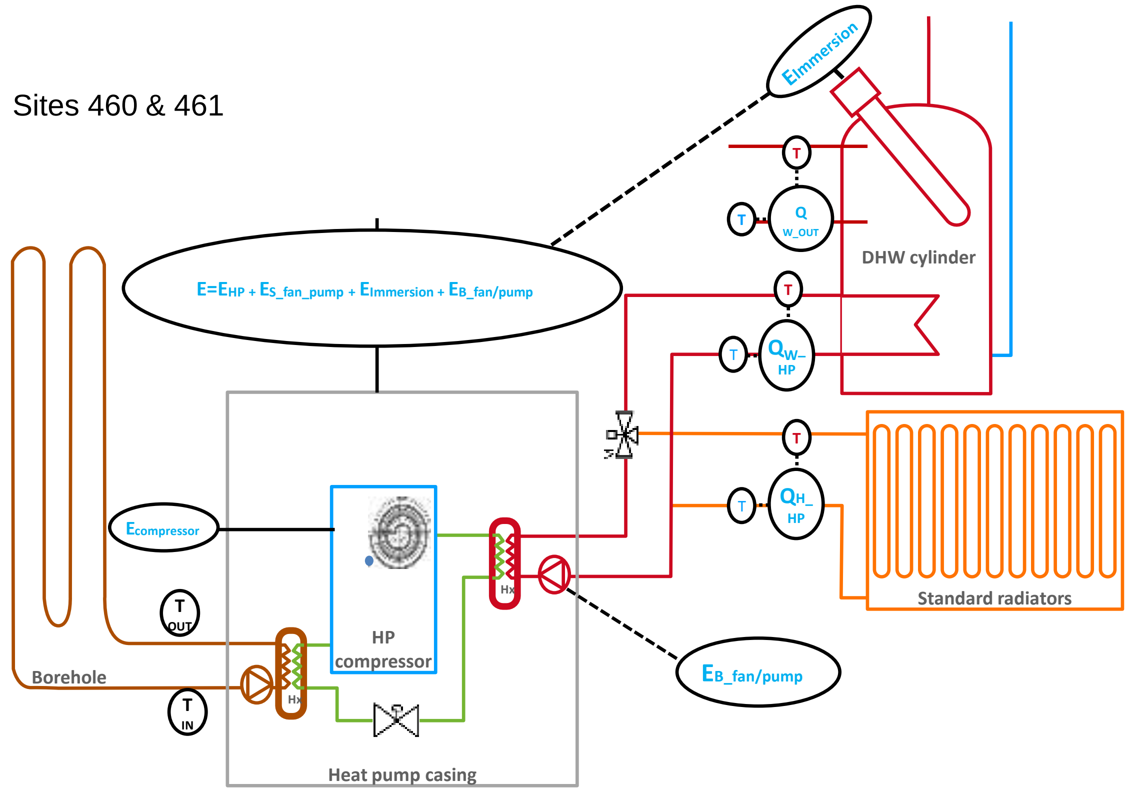


Figure 64: Schematic for site 460, Phase II

5.6.1. SPFH1-4 and System Efficiency

Table 30 shows the seasonal performance factors and system efficiency. It can be seen that there was only a slight improvement in temperature corrected system efficiency during Phase II.

	SPF_{H1}	SPF_{H2}	SPF_{H3}	SPF_{H4}	System efficiency	Temperature corrected system efficiency
Phase I					2.32	2.32
Phase II	(3.60)	(3.15)	3.03	2.86	2.41	2.50

Table 30: Seasonal performance factors and system efficiency for site 460, Phase I & II

Note a small difference between SPF_{H2} and SPF_{H3} due to use of the domestic hot water immersion during two summer months.

5.6.2. Space and Water Heating Efficiency

The heat pump was designed to use a refrigerant that enables production of domestic hot water at suitable temperatures, obviating the need for immersion. Figure 65 shows a scatterplot of SPF_{H2}, separated by space and domestic hot water heating. The site shows excellent SPF_{H2} (between 3 and 4 for space heating, depending on ambient temperature, and between 1.8 and 2.6 for water heating), although a handful of points show very low efficiencies for water heating; these occurred when the flap valve was faulty.

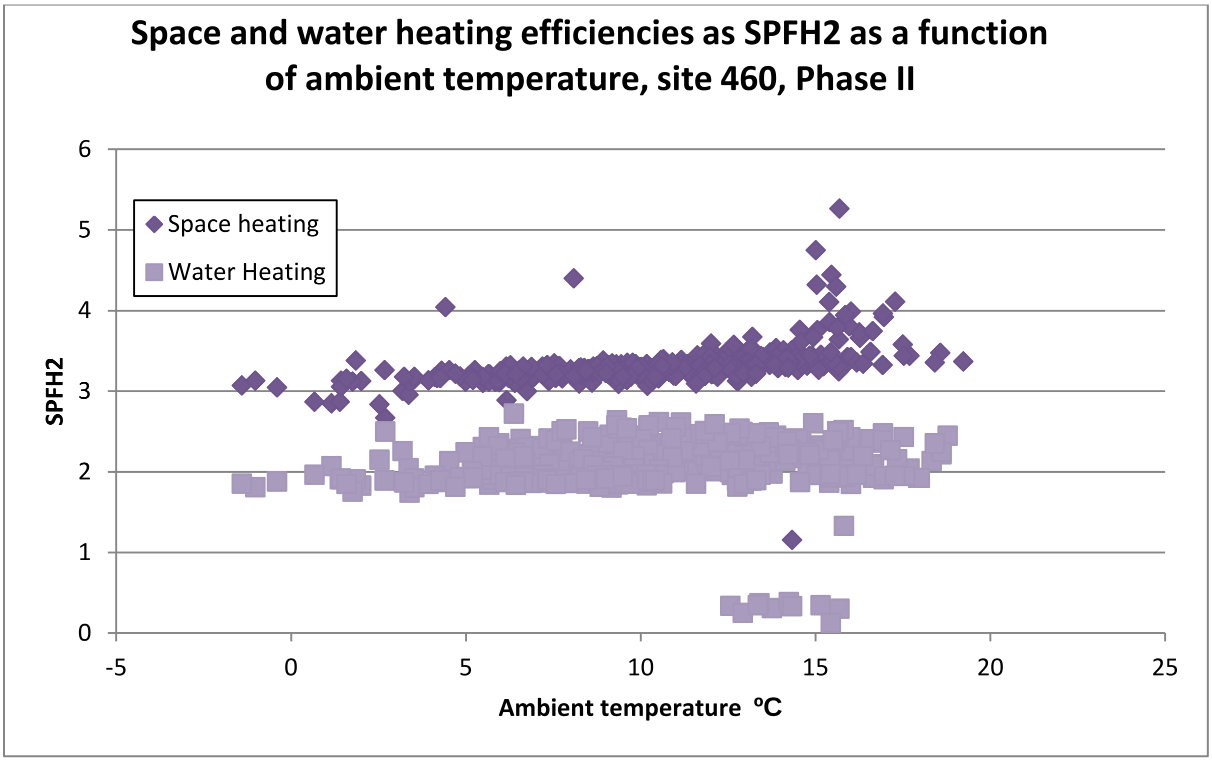


Figure 65: Space and water heating efficiencies (as SPFH2) as a function of ambient temperature at site 460, Phase II

Table 31 summarises the data; this is an excellent example of how heat pumps can be configured to produce good efficiencies for both space and water heating. Note, however, that even a good water heating efficiency has the effect of reducing the overall efficiency as compared to the value that would be obtained if there were no water heating. This underlines the importance of stating clearly whether a given quoted efficiency applies only for space heating or whether it also applies to water heating.

	SPF_{H2} space heating	SPF_{H2} water heating	SPF_{H2} (overall)
Phase II	(3.53)	(2.07)	(3.15)

Table 31: Space and water heating efficiencies for site 460, Phase II (as SPF_{H2})

6. Case Studies (Minor changes)

This section presents examples for which minor interventions were carried out between Phases I and II.

6.1. Air-source Heat Pump Supplying Radiators, Site 443

At this 2 bedroomed semi-detached bungalow, an 8.2 kW air-source heat pump supplies heat to radiators only. Figure 66 shows the schematic.

Sites 443 & 444

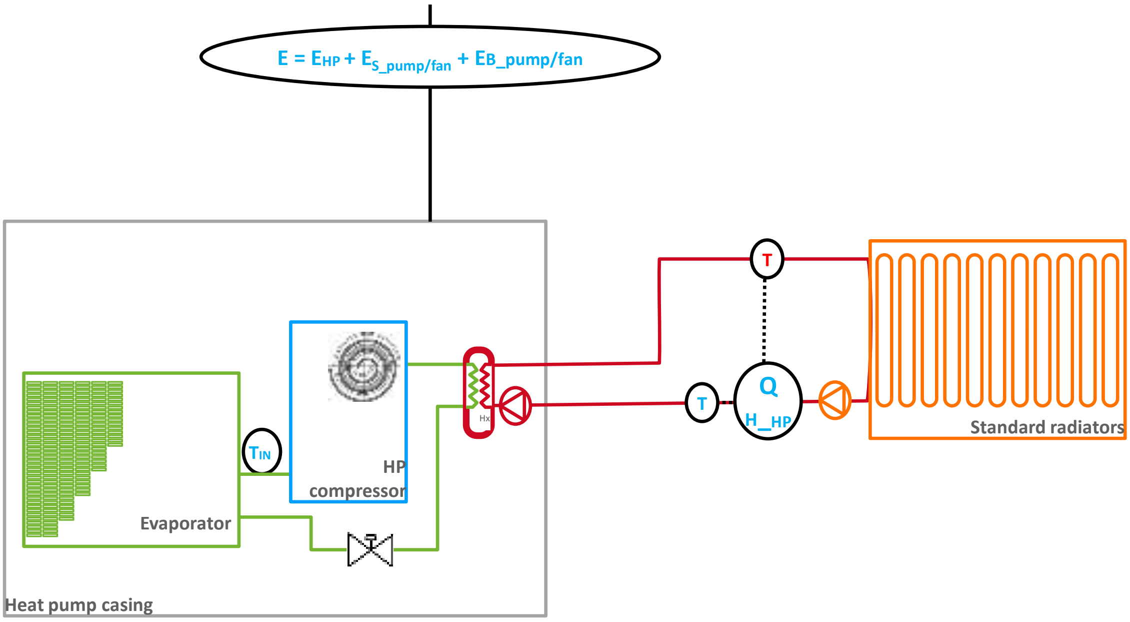


Figure 66: Schematic for site 443, Phase II

For Phase II, various changes were made to the controls, including:

- replacing the defrost sensor
- replacing the controller unit
- re-instating weather compensation
- increasing the temperature differential between flow and return temperatures from 3°C to 5°C.

6.1.1. SPFH1-4 and System Efficiency

For this site, there are no separate measurements of the electricity used by the compressor. SPF_{H1-H3} have been estimated by inspection of the time series of electricity demand, but these estimates are necessarily less accurate than when compressor data is available. For this site, which has no domestic hot water production, the system efficiency is equal to SPF_{H4}. Table 32 shows the results.

	SPF_{H1}	SPF_{H2}	SPF_{H3}	SPF_{H4}	System efficiency	Temperature corrected system efficiency
Phase I	N/A	N/A	N/A	2.29	2.29[13]	2.29
Phase II	(2.41)	(2.30)	(2.30)	2.25	2.25	2.24

Table 32: Seasonal performance factors and system efficiency for site 443, Phases I & II

There is no perceptible difference in performance following the interventions, as shown in the scatterplot of SPF_{H4}, Figure 67.

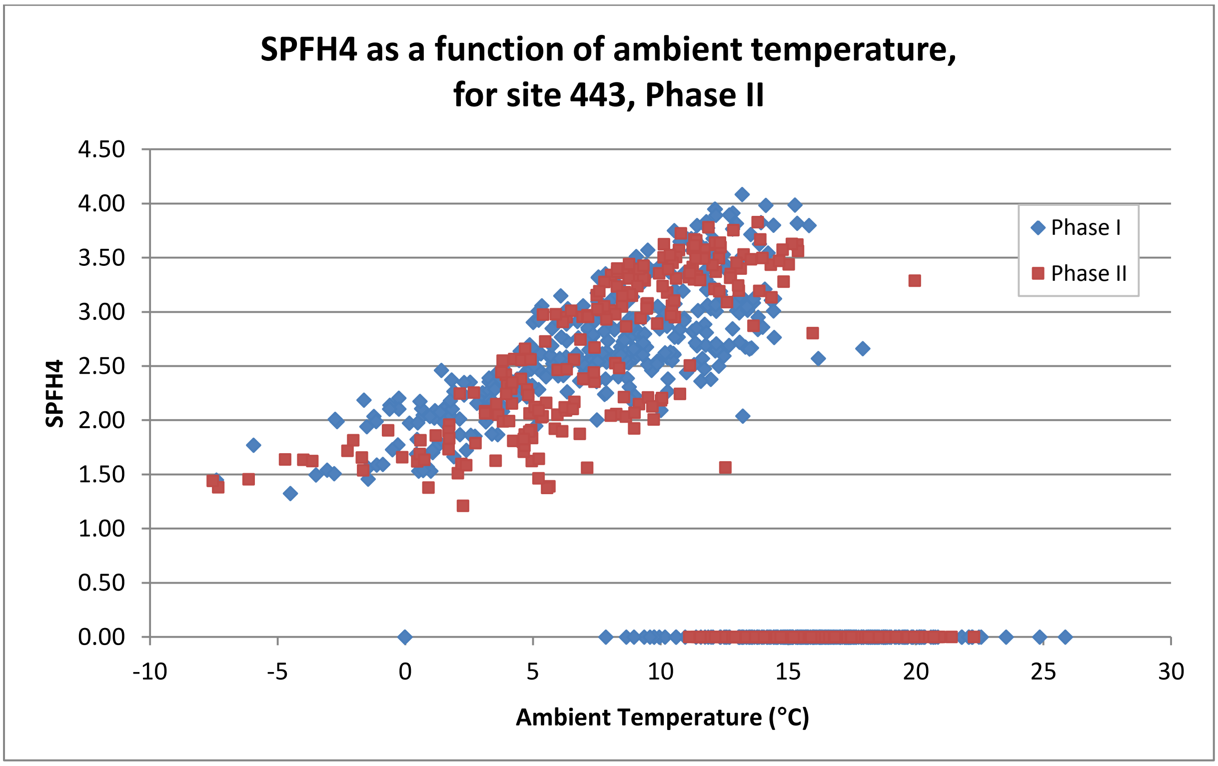


Figure 67: SPF_{H4} as a function of ambient temperature for site 443, Phases I & II

[13] Note a slight reduction in reported system efficiency since the phase I report (reference [1]), where a figure of 2.41 was quoted. This is due to removal of a small amount of faulty data.

7. Case Studies (New sites)

This section presents results from some of the six sites added to the sample for Phase II.

7.1. Air-source Heat Pump Supplying Fan-Assisted Radiators and Domestic Hot Water, Site 448

Site 448 is an 11 kW air source heat pump installed in a mid-terraced, solid wall house. It supplies fan assisted radiators (via a buffer tank) and domestic hot water. Figure 68 shows the schematic.

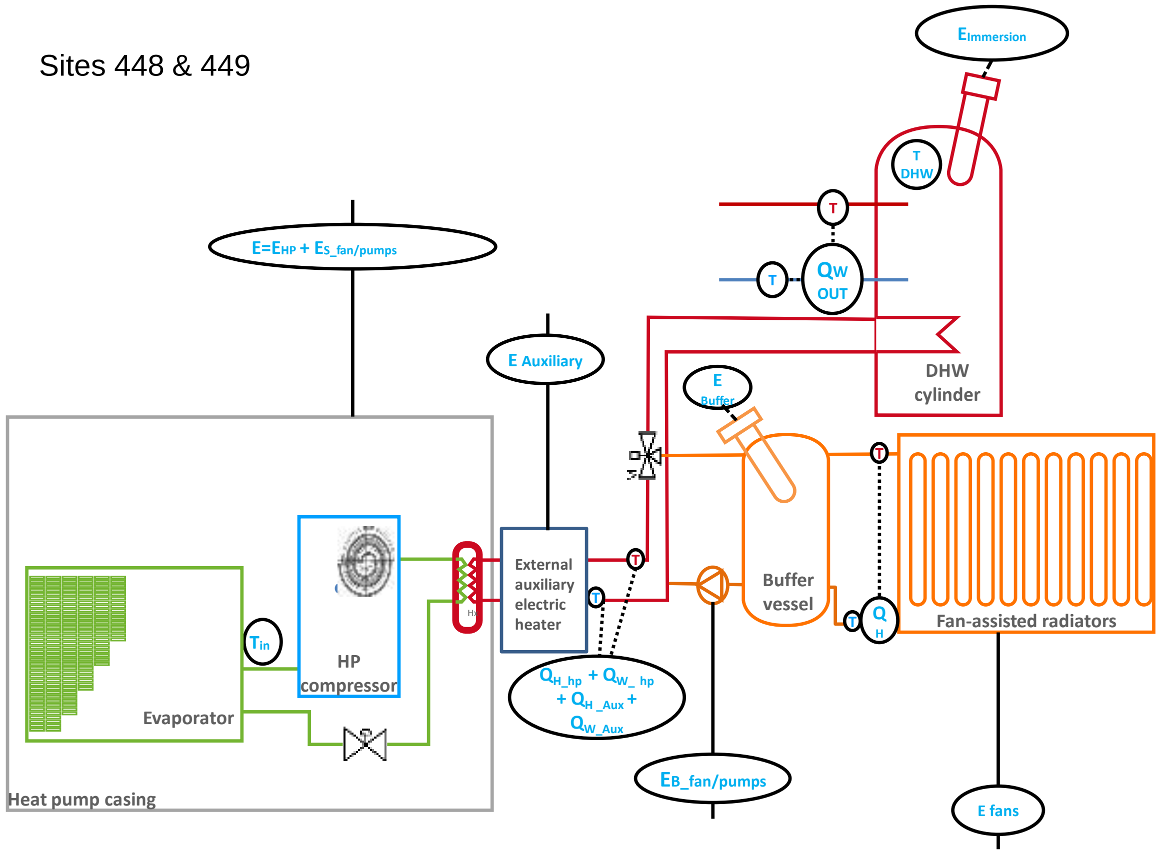


Figure 68: Schematic for site 448, Phase II

The site is equipped with five electricity meters:

- heat pump
- radiator fans
- circulation pumps
- buffer tank immersion

- domestic hot water immersion

And three heat meters:

- from the heat pump
- from the buffer tank to the central heating
- from the domestic hot water tank.

7.1.1. SPFH1-4 and System Efficiency

The seasonal performance factors and system efficiency for site 448 are shown in Table 33 and Figure 69.

	SPF_{H1}	SPF_{H2}	SPF_{H3}	SPF_{H4}	System efficiency	Temperature corrected system efficiency
Phase II	N/A	2.79	2.55	2.16	1.85	1.90

Table 33: Seasonal performance factors and system efficiency for site 448, Phase II

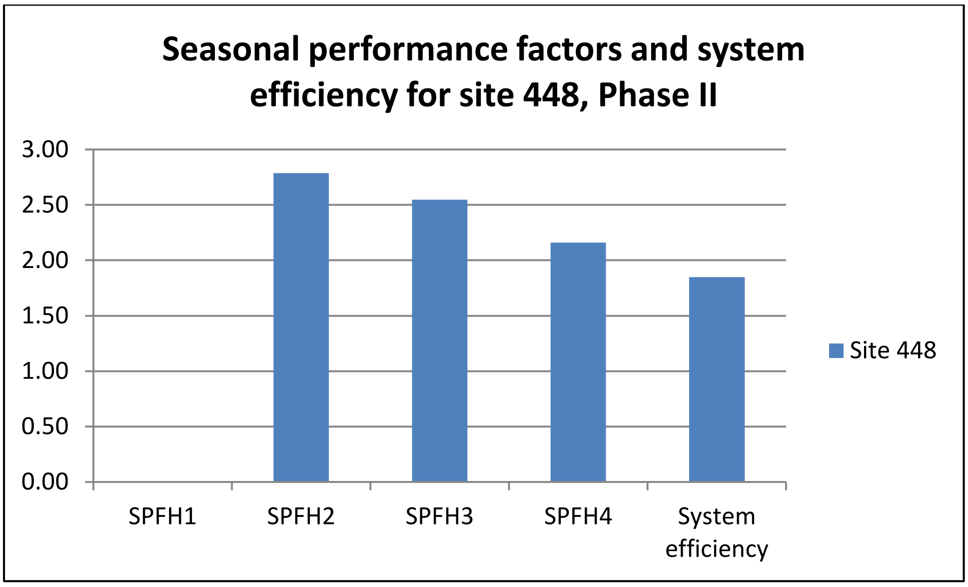


Figure 69: Seasonal performance factors and system efficiencies for site 448, Phase II

Overall, performance is disappointing; SPF_{H2} is in the middle of the range of the air-source systems monitored (2.79) despite the use of fanned radiators. Significant use of the domestic hot water immersion and circulation pumps account for the low SPF_{H4}. This is examined further in section 7.1.2.

The use of fanned radiators permits low central heating temperatures and so, in principle, would be expected to result in good performance. Figure 70 shows central heating temperatures of between 30 and 45˚C for a winter's day in which the ambient temperature was between -2 and +8˚C.

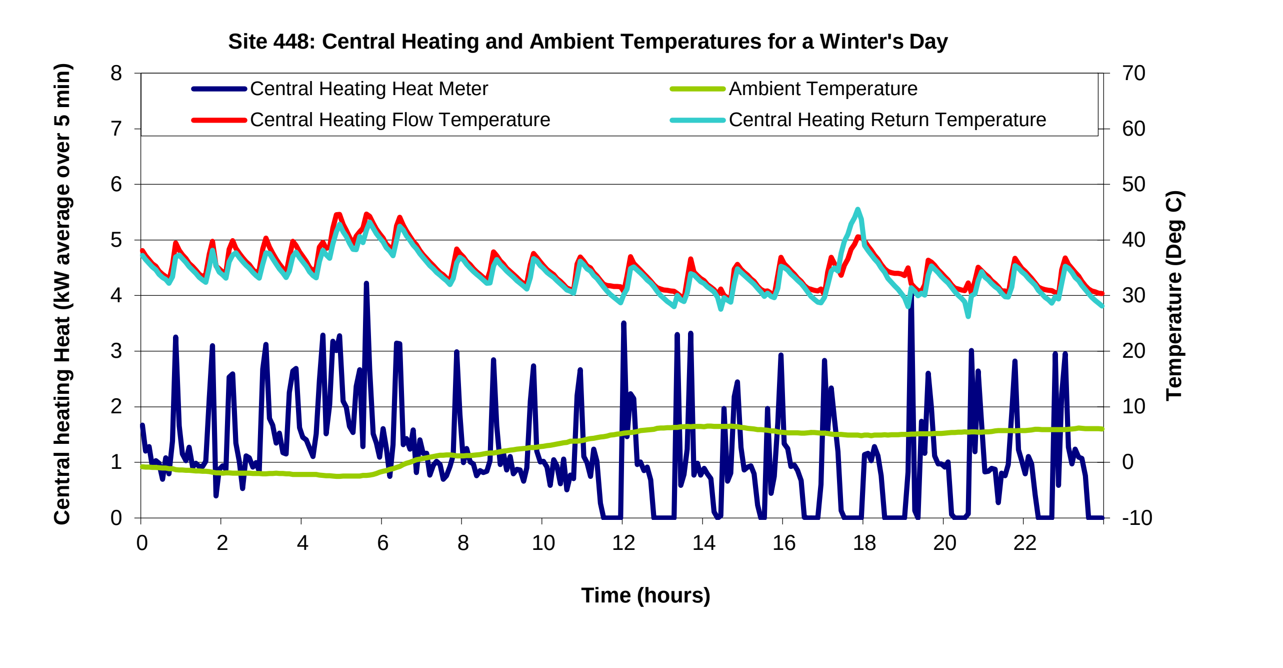


Figure 70: Central heating flow and return temperatures and ambient temperatures on a typical winter's day for site 448, Phase II

7.1.2. Electricity consumption by component

Table 34 and Figure 71 show the electricity consumption by component.

	Heat pump (includes inlet fan; no auxiliary heating)	Domestic hot water immersion	Buffer tank immersion	Circulation pump on central heating side	Fanned radiators
Electricity consumption (kWh)	2715	419	0	562	157

Table 34: Electricity consumption by different components for site 448, Phase II

Note the very high consumption of the circulation pumps on the central heating side (15% of the total) and the lower, but significant consumption of the fanned radiators.

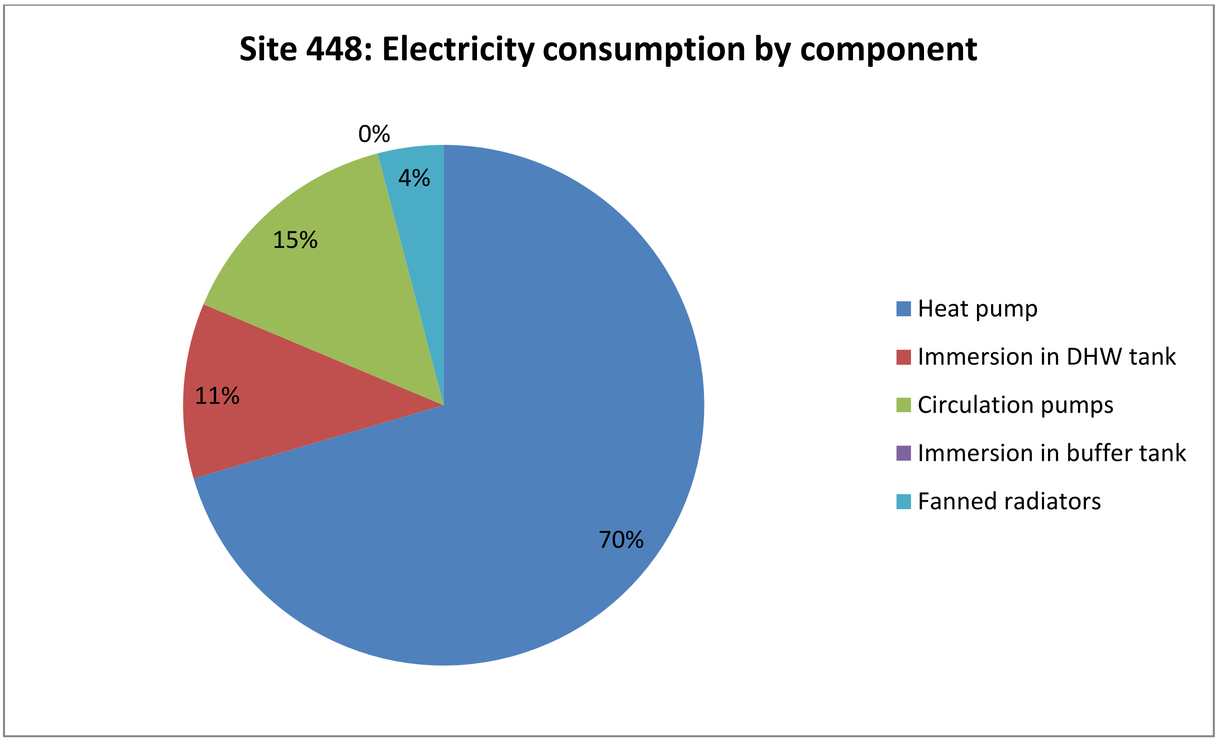


Figure 71: Electricity consumption by different components for site 448, Phase II

The scatterplot of SPF_{H2} and SPF_{H4} against ambient temperature shows the effect of the domestic hot water immersion, the fan-assisted radiators and the high consumption of the circulation pumps on efficiency (Figure 72). This is another example of where integral monitoring of the electrical consumption of each component could be used to improve efficiency.

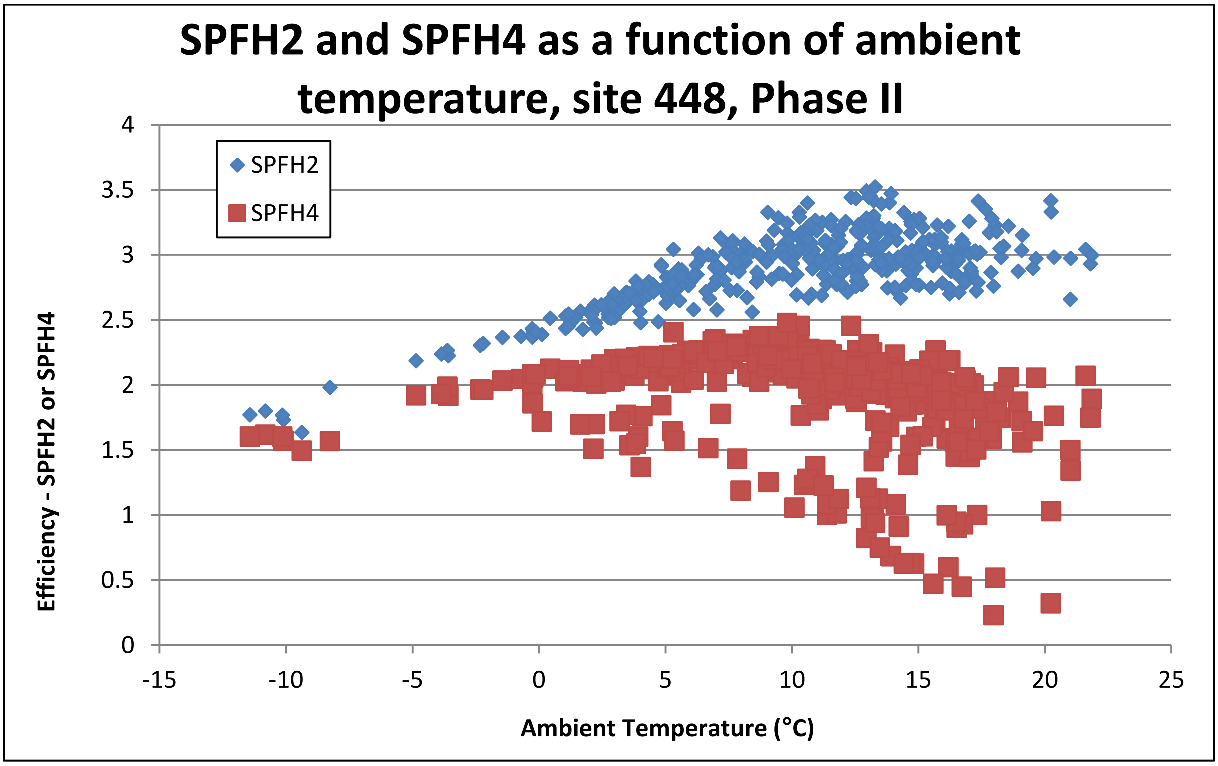


Figure 72: SPF_{H2} and SPF_{H4} as a function of ambient temperature for site 448, Phase II

7.1.3. Defrost

There is very significant defrost at this site (544 kWh, or 7% of the total heat delivered, taken as reverse heat flow, rather than direct electric consumption). Defrost is observed during every month of the year, reaching 11% of total heat delivered in July, as shown in Figure 73. This illustrates the importance of ensuring that defrost functions are configured correctly.

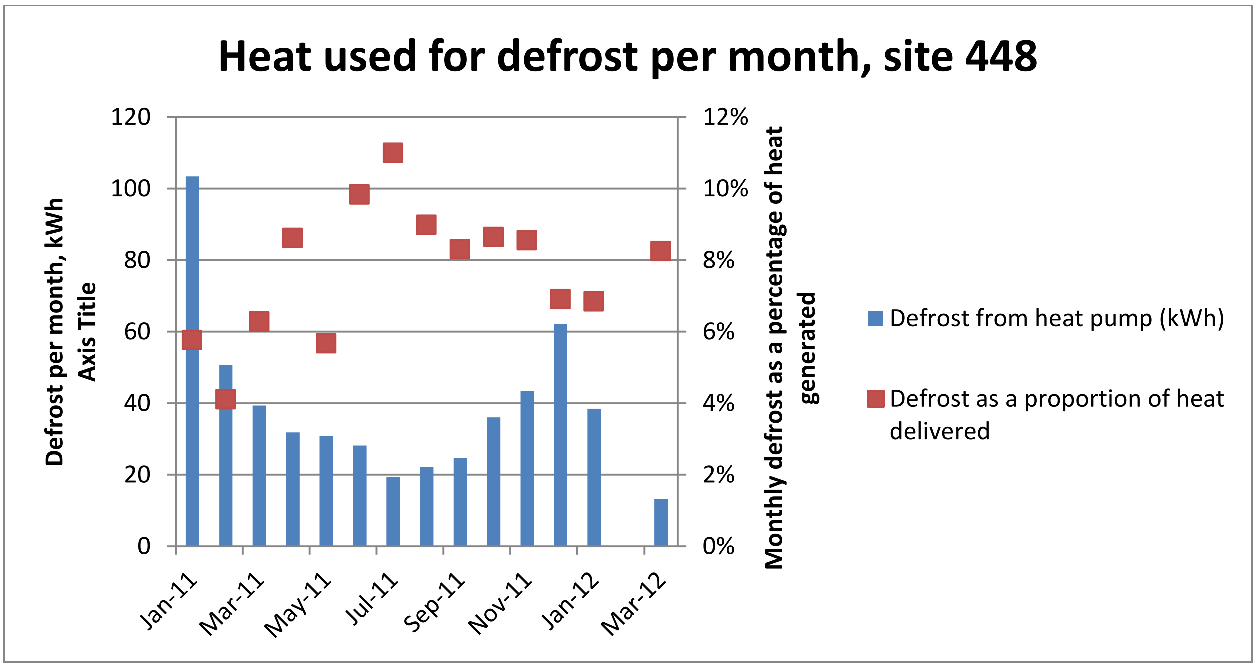


Figure 73: Heat used for defrost per month, site 448, Phase II

7.2. Air-source Heat Pump Supplying Fan-Assisted Radiators and Domestic Hot Water, Site 449

This site is identical to site 448. An 11 kW air source heat pump supplies fan-assisted radiators and domestic hot water for a solid walled terraced house.

7.2.1. SPFH1-4 and System Efficiency

The seasonal performance factors and system efficiency for site 449 are shown in Table 35.

	SPF_{H1}	SPF_{H2}	SPF_{H3}	SPF_{H4}	System efficiency	Temperature corrected system efficiency
Phase II	N/A	2.76	2.57	2.26	1.73	1.74

Table 35: Seasonal performance factors and system efficiency for site 449, Phase II

7.2.2. Electricity consumption by component

Figure 74 shows the breakdown of electricity consumption by component. For this site, the circulation pumps and fan-assisted radiators account for a high proportion of consumption (11% and 10% respectively).

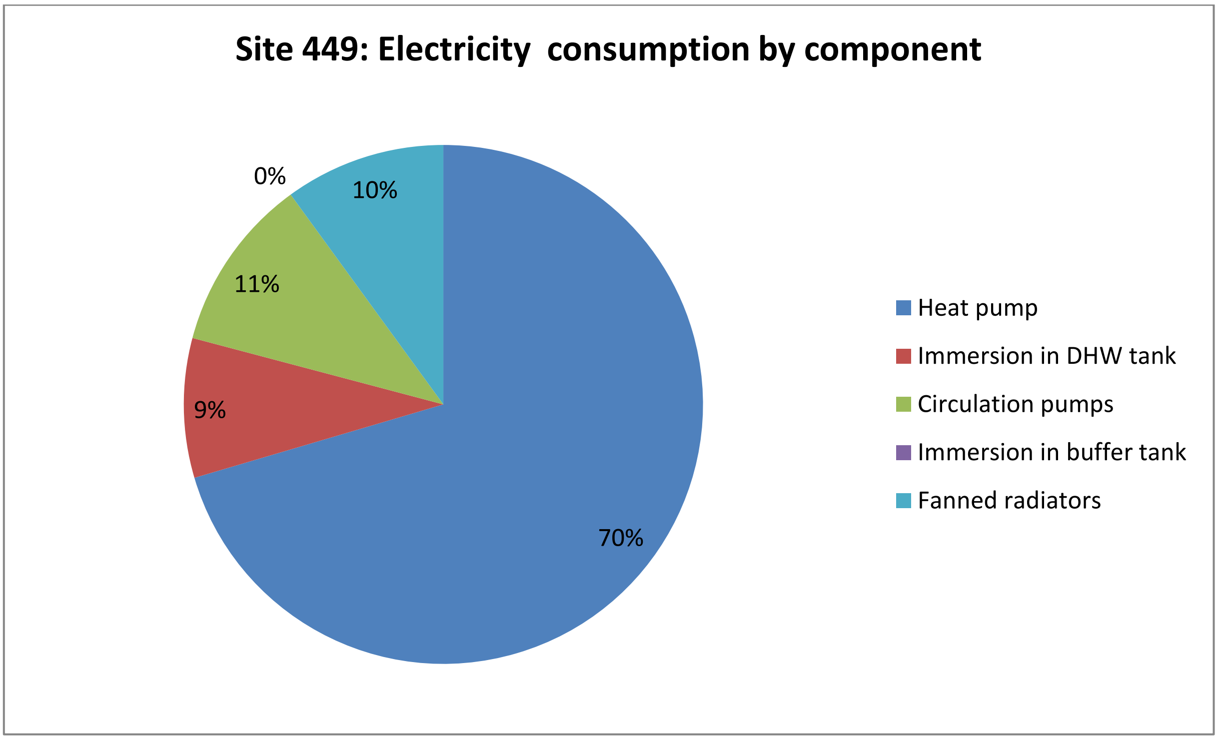


Figure 74: Electricity consumption by different components, site 449, Phase II

8. Summary and Conclusions

This section presents the conclusions from the analysis presented in sections 3-7.

8.1. Discussion of System Boundaries

There are many different ways of defining the efficiency of a heat pump.

The COP (coefficient of performance), is defined as the heat output of the heat pump, divided by the sum of the electricity used by the compressor plus a proportion of the electricity required to overcome head losses in the heat source pump or fan and heat sink pump or fan. **COP[14] is measured in a laboratory at specific temperatures** (for the heat source and sink) according to EN-14511.

[14] Note that, in the first year report, the notation COP has been used to refer to the seasonal coefficient of performance. The notation "COP" for seasonal coefficient of performance has been avoided in this report

The **seasonal coefficient of performance** for **any given climate**, $SCOP_{ON}$, may be calculated from the COP values according to the procedures outlined in EN-14825.

However, there are many other ways to define the seasonal performance of a heat pump, depending on the system boundaries, i.e. which parameters are included in the electricity input and heat output. A detailed and thorough assessment was carried out under the EU-SEPEMO project, which defined four efficiencies, $SPF_{H1\text{-}H4}$ as shown in Table 7 and reproduced in part in Table 36:

	Component	EN 14825 $SCOP_{NET}$	SPF_{H1}	SPF_{H2}	SPF_{H3}	SPF_{H4}
Heat	Heat supplied by heat pump	x	x	x	x	x
	Heat supplied to central heating circuit					
	Heat supplied to domestic hot water cylinder					
	Heat extracted from domestic hot water cylinder					
Electricity	Compressor	x	x	x	x	x
	Heat source fan/ pump	head losses	---	x	x	x
	Back-up for both space heating and domestic hot water	--	---	---	x	x
	Buffer tank pump	---	---	---	---	x
	Space heating and domestic hot water fans/pumps	head losses	---	---	---	x

Table 36: System boundaries for a selection of seasonal performance factors

The MCS 022 Heat Emitter Guide estimates SPF_{H4}, i.e. it includes both auxiliary electric heating and electricity consumption by circulation pumps; however, it refers to space heating only.

In Phase I of the Energy Saving Trust field trials, the monitoring configuration was designed to assess "system efficiency". This differs from the seasonal performance factors shown above in that the heat output is considered to be the sum of the heat supplied to the central heating circuit and the heat in the hot water actually consumed by the householder (i.e. after heat losses from the domestic hot water tank have been taken into account). This definition was chosen to be consistent with the condensing boiler field trial report; it is also more appropriate for systems with integral domestic hot water tanks. The definition was approved by the funding board and also by the peer review panel.

In Phase II of the Energy Saving Trust field trials, additional monitoring has been undertaken, to allow the calculation of other measures of efficiency. This enables us to a) compare with manufacturers' declared estimates $SCOP_{ON}$ (very similar to SPF_{H2}) and b) to identify the effect of electrical consumption by ground pumps, auxiliary heaters, immersion heaters and circulation pumps or fans.

Table 37, taken from one of the heat pumps in the trial, shows four separate estimates of the seasonal performance factor. It can be seen that there is a reduction of around 1 from SPF_{H1} to

SPF_{H4} and a further reduction when system efficiency is calculated. As this example illustrates, it is **essential** to define which system boundaries are being used when referring to seasonal performance factors.

	SPF_{H1}	SPF_{H2}	SPF_{H3}	SPF_{H4}	System efficiency	Temperature-corrected system efficiency
Phase I	N/A	N/A	N/A	2.26	1.82	1.80
Phase II	(3.59)	(2.94)	(2.81)	2.64	2.28	2.35

Table 37: Example of seasonal performance factors and systems efficiency for one of the heat pumps in the trial

Temperature-corrected system efficiencies have been used to compare data from Phase I with data from Phase II.

This study concludes that SPF_{H4} is the most appropriate metric for comparing the efficiency of heat pump systems; it gives a good indication of the combined quality of the product and the installation and is not adversely affected by the householders' domestic hot water consumption, as system efficiency is.

8.2. Summary of Results

The second year of the heat pump field trials has demonstrated that carefully designed and installed systems achieve good performance.

38 systems from the first phase were modified and six new systems were added. A range of configurations were covered:

- Ground and air-source;
- Standard radiators, low temperature radiators and underfloor heating;
- With and without domestic hot water provision
- Integrated and separate domestic hot water tanks
- With and without buffer tanks.

Modifications were divided into four categories:

- Major: Replacing the heat pump, reducing the area heated by the heat pump, repairing leaks to ground loops and re-charging refrigerants (12 sites). The most common modification was re-sizing the heat pump; however, sizing was carried out according to the manufacturers' procedures at the time and therefore the replacement heat pumps were not necessarily compliant with MCS MIS 3005 Issue 3.1. Nine heat pumps were replaced and one system was changed so that the heat pump heated a smaller area, which is equivalent to re-sizing the heat pump.

- Medium: Re-filling the ground loop, installing a buffer tank, replacing a hot water tank, connecting a shower unit to the heat pump, replacing radiators, replacing circulation pumps, installing a voltage optimiser, mending or replacing a flap valve, replacing manifolds (9 sites). The most common modification was replacing the circulation pumps (eight out of nine sites).
- Minor: Altering control parameters, disabling auxiliary electric heater, adding insulation to pipes (11 sites)
- None (6 sites).

The six new sites were all air-source and were designed and installed to be compliant with the MCS MIS 3005 Issue 3.1 guidelines.

8.2.1. Temperature-corrected system efficiencies in Phases I and II

System efficiencies from the first and second phases were compared, after correcting for temperature.

Nine out of 12 heat pumps with major modifications showed improvements in system efficiency from Phase I to Phase II. Of these, eight showed an improvement of ≥0.3. For two of the three sites for which system efficiency was reduced in Phase II, the reason was increased immersion consumption for domestic hot water.

Eight out of nine heat pumps that received medium interventions showed improved system efficiencies in Phase II. In five cases, the improvement was ≥0.3. The greatest improvement, from 2.31 to 3.29, was at a site where software was altered to reduce the use of the auxiliary heater. The remaining heat pump in this category developed a fault during the second phase.

These substantial improvements in system efficiency indicate that problems have been rectified.

11 heat pumps received minor interventions; usually a service and or change of control strategy. Only one showed a significant improvement in system efficiency (0.3), while, for six of the sites, the magnitude of the difference in system efficiency was less than 0.1. The remaining three sites showed a decrease in performance of around 0.2.

Closer examination of these sites indicated that, for two of these three sites, the proportion of domestic hot water used in the second phase had increased significantly, thereby decreasing the perceived overall system efficiency.

6 heat pumps were not modified. The system efficiencies for Phases I and II were unchanged.

8.2.2. SPFH4

SPF_{H4} takes account of all the electricity used by the heating system and therefore is the most appropriate measure of efficiency for householders to understand the costs and benefits of running a heat pump. It was possible to calculate SPF_{H4} values for 15 air-source and 22 ground-source systems in the trial. The average SPF_{H4} values were found to be 2.45 ± 0.11 and 2.82 ± 0.10 for air- and ground-source respectively.

8.2.3. SPFH2 and the EU Renewable Energy Directive

The case studies generally indicate good performance as measured by SPF_{H2}, with mean values being 2.68 (for 15 air-source heat pumps) and 3.10 (for 21 ground-source heat pumps).

Nine of the 15 air-source heat pumps for which SPF_{H2} could be calculated had an $SPF_{H2}>=2.5$, thereby fulfilling the EU Renewable Energy Directive criterion to be considered renewable. **Of these nine compliant air-source heat pumps, five were new heat pumps, designed, sized and installed according to the MCS MIS 3005 Issue 3.1.**

20 out of 21 ground-source heat pumps met the criterion to be considered renewable.

8.2.4. Space heating efficiency

In 34 cases (14 air-source and 20 ground-source), it was possible to calculate SPF_{H2} for space heating. The average space heating efficiencies, as SPF_{H2}, were found to be 2.73 for the air-source heat pumps and 3.21 for ground-source heat pumps.

8.2.5. Water heating efficiency

In 27 cases, it was possible to calculate SPF_{H2} for water heating. Excluding one outlier, the average SPF_{H2} for water heating was found to be 2.35 with no detectable difference between air and ground source heat pumps. It should, however, be noted that electric immersion heating is also required in most instances. Sterilisation schedules should be carefully configured to control bacteria effectively, whilst avoiding excessive use of electric immersion.

8.2.6. Auxiliary electricity usage and use of circulation pumps

Auxiliary electric heating, for both space and water heating, and consumption of electricity by circulation pumps on the central heating side account for the difference between SPF_{H2} and SPF_{H4}.

Several of the examples have shown high consumption by auxiliary heating (either space heating or domestic hot water immersion), or high consumption by circulation pumps on the central heating side. In the worst case, auxiliary heating supplied almost all the heat for 73 days, resulting in an increase in the householders' bills of approximately £350.

There are several examples of circulation pumps for the central heating system using too much electricity – around 500 kWh in one case.

Careful control of auxiliary electric heating and the use of low energy pumps can result in significant improvements to system efficiency; in one case, these two measures alone resulted in an improvement of system efficiency from 2.35 to 3.28.

The EU Eco-design directive limits the energy consumption of glandless circulation pumps for heating and air-conditioning as of January 2013. Further tightening of these regulations will require that circulation pumps integrated in heat pumps and boilers are energy efficient as of 2015.

8.2.7. Buffer tanks

Insertion of buffer tanks did not seem to reduce cycling in the examples in this trial. Buffer tanks are expected to be beneficial when the volume of water in the central heating system is very low. Under these circumstances, they can reduce rapid cycling for fixed speed compressors. Laboratory tests have confirmed that performance can be reduced significantly for cycling periods less than 6 minutes [5].

9. Recommendations

This section presents the principal recommendations from the study.

It is **essential** to define which system boundaries are being used when referring to seasonal performance factors. DECC considers that SPF_{H4} gives the best overall indication of the combined quality of a product and its installation and would therefore recommend that SPF_{H4} is used whenever possible. The MCS MIS Heat Emitter Guide requires the installer to provide the householder with an estimate of SPF_{H4} for space heating.

DECC proposes that MCS MIS 3005 should be amended to give guidance on the best way to heat domestic hot water with a heat pump, and that the estimated seasonal performance factors shown to the householder by the installer should be a weighted average of SPF_{H4} for space and water heating (if domestic hot water is supplied by the heat pump).

DECC would strongly recommend that the electricity used by auxiliary heater and domestic hot water immersion is measured and that appropriate diagnostics are given to the householder. We are aware that some manufacturers monitor the electricity consumption of each component of the heat pump and would encourage others to do so. DECC also considers that controls should be absolutely clear to the average householder. It is not sufficient to have a "winter" setting which activates the auxiliary electric heating.

Software controlling the sterilisation pattern should be carefully configured so that the immersion is not used excessively. There is a case for research projects to investigate alternative methods of controlling bacteria such as Legionella.

For air-source heat pumps, software controlling defrost should be carefully configured so that defrost is used only when required. Appropriate diagnostics should be provided to the householder.

The EU Eco-design directive limits the energy consumption of glandless circulation pumps for heating and air-conditioning as of January 2013. Further tightening of these regulations will require that circulation pumps integrated in heat pumps and boilers are energy efficient as of 2015.

There is a case for laboratory experiments to determine whether significant savings can be made if a voltage optimiser is used.

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11. Appendix A: Instrumentation used

The monitoring and data logging equipment installed in each house was specified in the Energy Saving Trust's technical monitoring specification for Phase I of the EST field trial. This was supplemented in Phase II of the trial by additional metering installed, wherever feasible, to allow the total heat output of the heat pump to be measured along with the power consumption of auxiliary heaters; thus allowing calculation of some or all of SPH_{H1} to SPH_{H4} (as well as the system efficiency measured in Phase I). The Phase II metering generally consisted of the following.

- generation II radio telemetry wireless data logger with associated:
  - GSM modem
  - SIM card
- electric meters on:
  - electric supply to heat pump
  - immersion heater in domestic hot water tank
  - sink/circulation pump
  - heat pump compressor (where possible) (allowing inference of auxiliary heater use)
- heat meters for:
  - space heating
  - domestic hot water (heat and flow rate)
  - either a heat meter on the total output from the heat pump (bidirectional for measuring the reverse cycle defrost on air-source heat pumps) or a heat meter measuring the heat into the domestic hot water cylinder (depending on space/ease for fitting)
- additional heat meters were installed at some sites, including
  - a ground loop heat meter at a few of those sites with accessible ground source loops (to enable heat balances to be undertaken).
  - heat meters measuring additional heat sources/sinks (e.g. systems with both under-floor heating and radiators).
  - a heat meter measuring the energy lost from continuously pumped domestic hot water supplies (this was only the case at a few of the larger properties with long pipe-runs between the domestic hot water cylinder and the taps).

- three wireless, single-point, temperature transmitters
    - external ambient (on the North side of the property)
    - living room
    - upstairs (main bedroom)
- wireless, multi-point, temperature transmitters, with sensors strapped to pipe-work, measuring temperatures on:
    - flow and return pipes on the sink at all sites
    - flow and return pipes on the central heating at all sites
    - flow and return pipes on the ground source, or two air-off temperatures on the air source, at all sites
    - domestic hot water temperatures: cold feed, hot water out and tank temperature where the heat pump supplies domestic hot water.
    - ground temperature sensors were installed where the physical conditions were suitable (i.e. the positioning of the ground source loop was known, drilling could be carried out safely and the instrumentation would remain undisturbed).
- wireless pulse counting transmitters collecting the outputs from:
    - electricity meters
    - heat meters

All meters were purchase new for this project and are of fiscal quality. Heat meters are manufactured to the EN 1434 standard and sold as a complete legal entity.

Figure 75: Generation II wireless data logger and transmitters

Checks were carried out on one of each type of heat meter used in the project (UH50, Sontex and Metrima), comparing the heat meter performance against an electrical flow boiler, with the electricity consumption metered using one of the trial electricity meters. Agreement was between 98% and 100% in all cases (that is the heat meter reading was less than the electricity meter reading – probably due to small heat losses from the flow boiler in the test rig).

On previous similar field trial projects, calibration certificates for the heat meters were obtained from the manufacturer. These calibration certificates show that the heat meter manufacturers select matched pairs of temperature probes for each meter, with errors of between 0.1 and 0.3 K at a flow and return temperature difference of 10°C (a sample of 120 meters). Larger percentage errors are possible at lower temperature differences, but this will only significantly affect ground loop heat meters; these are used only for heat balances (see Appendix B), and the heat balances obtained are good. Accuracies are always significantly better than those required by EN 1434. This requires maximum permissible error to be less than +/-5%.

Heat meters have been shown to give erratic, erroneous readings when air (or another gas) is present in the circulating water flows. A SpiroVent – a particular brand of in-line de-aerator – was fitted as a preventive measure to sites where it was considered likely that a heat meter might experience air within the water flow, and where no other type of de-aerator had already been fitted. SpiroVents were also retrofitted to a few sites that experienced erratic heat meter readings after the start of the trial. Where SpiroVents were installed, they were located in the flow from the heat pump, at the highest point in a circuit. Further details of the monitoring equipment are shown in Table 38.

Measurement	**Meter**	**Sensor Resolution**	**Accuracy**
Heat Meter	Landis and Gyr UH50	1 Wh	Typically ± 2.5%
Bi-directional Heat meter	Metrima F27HC	100 Wh	Class 2
Bi-directional Glycol heat meter	Sontex	10 Wh	Class 3
Electric meters	Class 1 Manufactured; Class 2 Ofgem approved	1 Wh	± 2%
Pipe temperatures	Eltek	0.1°C	± 0.3°C
Room and ambient temperatures	Eltek	0.1°C	± 0.3°C

Table 38: Accuracy and resolution of instrumentation

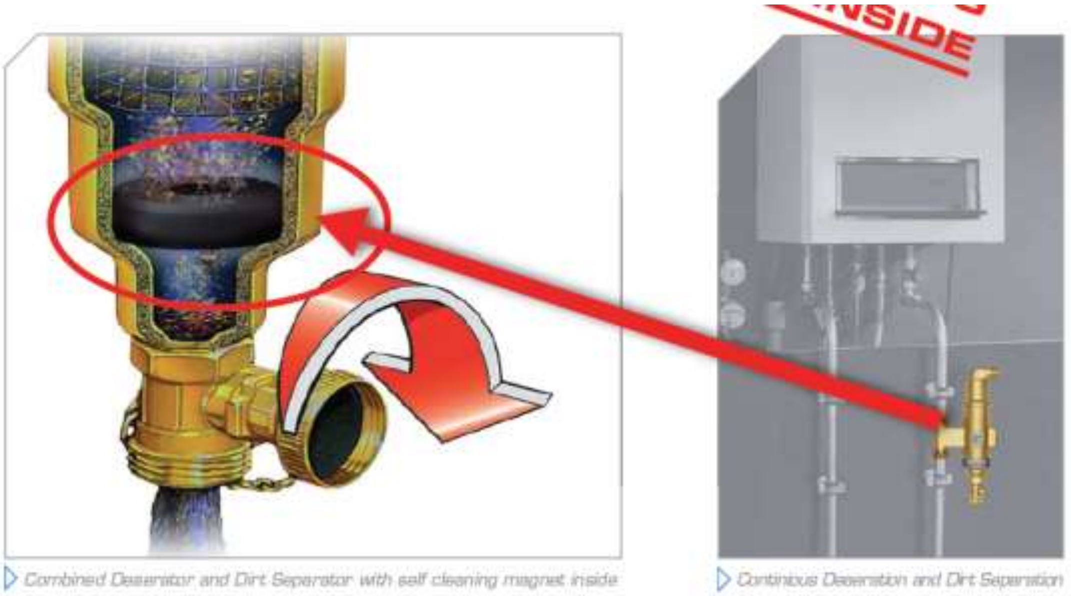

Figure 76: SpiroVent de-aerator

At temperature differences below the lower limit of 3°C, the manufacturer of the Landis and Gyr heat meter is unable to guarantee that the error remains within the EN 1434 standard; however, the meter still operates and records data when the temperature difference is less than this. The primary issue is the error on the platinum resistance thermometer (PRT) when measuring small temperature differences at relatively low temperatures. This would be an issue for any monitoring system using PRTs and a flow sensor. The advantage of using a heat meter is that the probes are a matched pair and are calibrated for the integrator unit. This helps to minimise errors. A possible alternative, the very high accuracy 1/10 DIN PRT, is generally only used within the laboratory environment because of high cost. The data monitoring team agreed before the trial that the combined heat meter solution would produce results at least equivalent to a system made up of separate temperature and flow sensors.

The equipment fitted on each site was determined on a site-by-site basis, dependent on the type of appliance installed and the configuration of the system.

Although the original monitoring specification required data to be recorded once every 10 minutes, the data logging interval was set to 5 minutes throughout this trial to give greater compatibility of results with other trials undertaken by the Energy Saving Trust (including microwind, condensing boilers and solar water heating).

12. Appendix B: Procedures for data checking

EA Technology collected the 5-minute data from individual data loggers remotely via the GSM mobile phone network and stored the raw data in a database. These raw data were automatically checked for erroneous figures, 'no data' errors or major collection errors. Spurious readings were checked manually, and where it was clear that a reading was spurious, it was removed. A log was kept of such substitutions. The spurious readings were rare, and were generally caused by either corruption during the download process or the pulse counter within an individual pulse-counting transmitter reaching saturation (216) and resetting to zero.

Data received by Kiwa Gastec at CRE were processed automatically using a program written in VB Excel. This program aggregated the weekly data into monthly spreadsheets, with a separate sheet for each day, and added calculations relevant to the specific site and type of appliance installed. This enabled the whole month to be inspected visually in a summary page.

Specifically, the power in and heat out were summed up over the day and then over the month. On sites where the total heat output from the heat pump was measured, the heat pump seasonal performance factor (SPF) was calculated. The buffer cylinder and domestic hot water cylinder efficiencies were calculated, along with apparent system efficiency. This allowed for a quick visual inspection of the data and it was easy to spot any discrepancies between days. The degree day heating requirement was calculated from the ambient temperature and was used to check the heat supplied to the house against the heat demand of the house.

The dataset was processed weekly, as required by the technical monitoring specification, so that high level problems, such as an inability to contact a data logger or data errors within a logger, could be addressed quickly. The data were compared with previous months on a monthly basis as a further quality check. Inter-house checks were also made. Kiwa Gastec at CRE excluded erroneous data for the time stamp where the pulses lay outside the expected range.

On discovery of inconsistencies in data, missing temperature data channels are easily identified. However, missing pulse data channels are more difficult to recognise since they may show a value of zero, both during normal operation and when the channel output has a fault. Thus, if discrepancies were found in the efficiencies and inter-day comparisons, the 5-minute data were studied in detail to establish where the fault lay.

As faults were identified on sites, they were reported to the project managers at Kiwa Gastec at CRE and EA Technology. Problems of missing data were usually caused by transmitter batteries failing or by water damage to transmitters. This generally required a site visit to correct the fault, although householders at a few sites were taught to replace batteries themselves. Problems such as not being able to contact a site were given top priority and were generally solved by the householder resetting the data logger. All faults were logged.

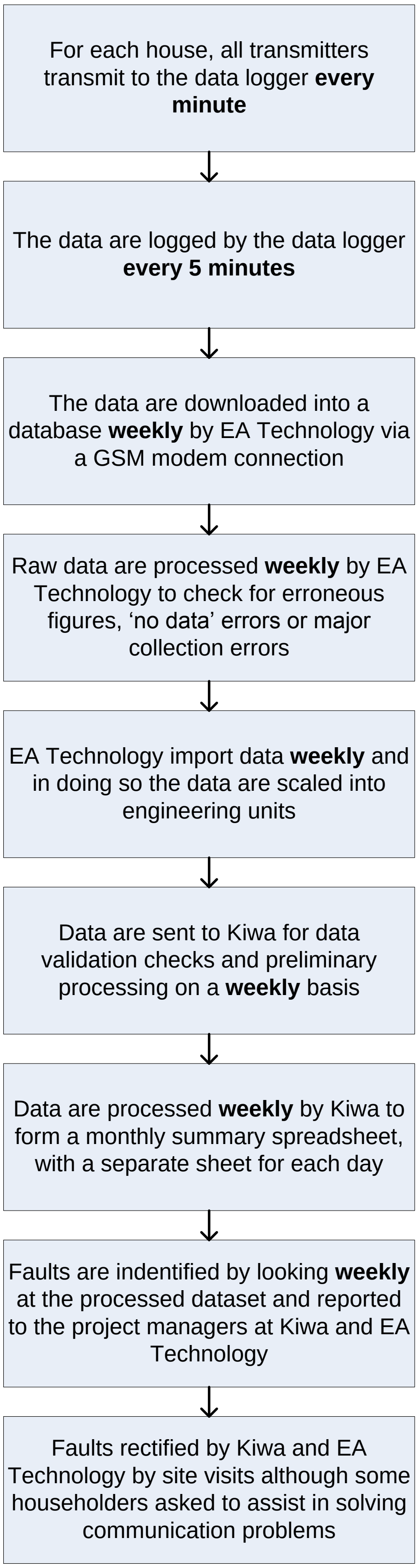

Figure 77: Flow chart showing procedures for data checking

12.1. Energy balance validation

Energy balances were undertaken on sites with ground source heat meters where the consistency of heat and electric meters over the heat pump can be calculated. This was undertaken on a weekly basis.

12.2. Data consistency checks

Further checks were carried out on the data during data analysis. There were a number of plots made for each site (using Excel and MATLAB) which were incorporated in reports shared with the heat pump manufacturers. The reports included:

- site descriptions and system schematics
- comparison system efficiencies from Phase I and II against ambient temperature
- where available, comparison of SPF3 or 4 from Phase I and Phase II against temperature
- distribution of system efficiency by month
- graphs of heat output versus electricity demand (indicating the parasitic electric use)
- heat pump power against the ambient temperature for varying central heating flow temperatures
- compressor maps
- plots of system temperatures (across the monitoring period)
- intra-day graphs (single day, detailed plots of all data)
- Morse code plots for non-system temperatures (plots across the monitoring period of room and ambient temperatures, alongside dashed lines indicating periods of heat pump operation)
- tapestries (showing the heating patterns for a particular month, as a series of blocks, colour coded for energy density, of heat and electricity use).

These plots were used to identify patterns and interesting features within the data and to inform the case studies. The plots were also used to highlight and confirm any errors with the data.

13. Appendix C: Methodology for the calculation of SPFH1-4 for different system configurations

13.1. System configurations

A wide range of different configurations were included in the Energy Saving Trust field trials, including:

- Systems providing central heating only
- Systems with no auxiliary electrical heater
- Systems with external domestic hot water tanks
- Systems with integral domestic hot water tanks.

13.2. Monitoring configurations

A range of monitoring systems was also used.

13.2.1. Location of heat meters

Wherever possible, heat meters have been placed either directly at the output of the heat pump, or at the inlet to the central heating and at the inlet to the domestic hot water tank. This applies to systems with both separate and integral domestic hot water tanks.

In some cases, only two heat meters were installed; one to monitor the total heat output of the heat pump and one to monitor the heat to the central heating. In this case, the time-series of heat flow was examined and the following procedure used:

- If space heating was produced, the heat pump electricity and total heat meter heat was attributed to space heating

- If no space heating was produced, the heat pump electricity and total heat meter heat was attributed to domestic hot water heating

In a few cases, a single heat meter was used to measure the heat to both the space heating and the domestic hot water tank. In these cases, the time-series of heat flow was analysed as follows:

- If space heating was produced with no domestic hot water heating, the heat pump electricity was attributed to space heating

- If domestic hot water heating was produced with no space heating, the heat pump electricity was attributed to domestic hot water heating

- If both space heating and domestic hot water heating were produced the heat pump electricity was split by the same proportion.

As per the specification in Phase I, heat meters have also been placed to measure the heat in the domestic hot water actually used by the householder.

13.2.2. Location of electricity meters

The number and placement of electricity meters is dependent on the configuration of the heat pump system. In broad terms, the configurations were as follows:

For systems supplying space heating only: a single electricity meter, which includes the electricity used by the compressor, the ground loop or fan (if air-source), the auxiliary heater (if present) and the circulation pumps on the heat sink side.

For systems with a separate domestic hot water tank: as above, but with an additional electricity meter to measure electricity used by the domestic hot water immersion.

For systems with an integral domestic hot water tank, the electricity meter for the heat pump includes the compressor, ground loop pump or fan (if air-source), combined auxiliary heater and domestic hot water and circulation pumps on the heat sink side. Additional measurements have been made of the electricity used by the compressor. In some cases, a third meter has been installed to monitor the electricity used by the circulation pumps on the heat sink side.

The electricity measurements for the principal system configurations are shown in Table 39

	System configuration			
Component monitored	**Space heating only, no internal auxiliary heater**	**Space heating only, with auxiliary electric heater**	**Space heating with auxiliary electric heater and separate domestic hot water tank**	**Space heating and integral domestic hot watertank**
Compressor	I	I	I	I and x
Brine fan/ pump	I	I	I	I
Auxiliary electricity for space heating only	N/A	I	I	N/A
Electric immersion for domestic hot water only	N/A	N/A	x	N/A
Auxiliary electricity for both space heating and domestic hot water (internal domestic hot water tanks only)	N/A	N/A	N/A	I
Buffer tank pump	N/A	N/A	N/A	N/A

Space heating and domestic hot water fans/pumps	I	I	I	I and x
Seasonal performance factors that can be calculated directly from the data	SPF_{H4}, system efficiency	SPF_{H4}, system efficiency	SPF_{H4}, system efficiency	SPF_{H1}, SPF_{H4}, system efficiency
Seasonal performance factors that can be estimated	SPF_{H1-H3}	SPF_{H1-H3}	SPF_{H1-H3}	SPF_{H2-H3}

Table 39: Electricity measurements of the principal system configurations in the trial

I = electricity use of component included in the measurement of electricity to the heat pump (referred to as E in this document; not referred to in SEPEMO, as the SEPEMO equations treat all electrical components separately).

x=separate monitoring of this component.

13.3. Procedure for calculation of seasonal performance factors

13.3.1. Space heating only, no auxiliary heater

Where possible, the rating of the pumps/fans on both the source and sink side have been obtained from the heat pump specification. The electricity consumption of the pumps/fans on the heat sink side ($E_{B\_pump/fan}$) can be estimated from the lowest consumption of the heat pump multiplied by the hours of use of the heating system.

The electricity consumption of the ground loop or fans on the source side ($E_{S\_pump/fan}$) can be estimated from the rating of these pumps/fans multiplied by the hours of use.

Equations [1-4] are used to estimate SPF_{H1}-$_{H4}$. Note that, in this case, SPF_{H2}=SPF_{H3} and SPF_{H4}=System efficiency.

Where the compressor has also been monitored, SPF_{H1} can be calculated directly, instead of being estimated.

13.3.2. Space heating only, with auxiliary heater

The heat versus electricity scatterplot and electricity time-series are used to identify periods when the auxiliary space heater is on and thereby to calculate E_{Aux}. Q_{H_aux} (from equation [3]) is equal to E_{Aux}.

$E_{B\_pump/fan}$ and $E_{S\_pump/fan}$ are estimated as before and equations [1-4] are used to estimate SPF_{H1-H4}.

Where the compressor has also been monitored, SPF_{H1} can be calculated directly, instead of being estimated.

13.3.3. Space heating and separate domestic hot water cylinder

The heat versus electricity scatterplot and electricity time-series are used to identify periods when the auxiliary space heater is on and thereby to calculate E_{Aux}. $E_{Immersion}$ is the electric immersion input to the domestic hot water tank and is monitored separately. Q_{H_Aux} is equal to E_{Aux} and Q_{W_aux} is equal to $E_{Immersion}$.

Where the compressor has also been monitored, SPF_{H1} can be calculated directly, instead of being estimated.

13.3.4. Space heating and integral domestic hot water cylinder

Additional heat meters have been installed to monitor heat flow to the domestic hot water in systems with integral domestic hot water tanks.

In these systems, a single electric cassette provides backup to both the space heating and the domestic hot water. In most cases, the electricity used by the compressor has been monitored. SPF_{H1} can therefore be estimated directly.

In some cases, the heat from the electric cassette has been monitored. This is referred to as Q_{Aux} on the relevant figures. This is equal to E_{Aux} + $E_{Immersion}$. In other cases, there is no measurement of Q_{Aux}, but the compressor has been monitored. E_{Aux}+$E_{Immersion}$ can be calculated from the scatterplots of heat versus electricity and time series of electricity consumption by the heat pump and compressor.

$E_{B\_pump/fan}$ and $E_{S\_pump/fan}$ are estimated as before, subject to the constraint that $E= E_{Aux}+E_{Immersion} + E_{B\_pump/fan} + E_{S\_pump/fan}+E_{compressor}$.

Where the electricity by the compressor has been measured, SPF_{H1} can be calculated directly. Both SPF_{H2} and SPF_{H3} are estimated (since $E_{S\_pump/fan}$ is estimated).

SPF_{H4} is calculated directly in all cases.

14. Appendix D: Procedure for temperature correcting system efficiencies (SEFF)

In order to accurately compare system efficiencies between phase I and II it is necessary to remove the influence of the variations in external temperature between the two monitoring periods. This process is known as temperature or weather correction.

The method used for the study utilised degree-day data. Degree-days are a comparative metric of the amount of energy required for heating to reach a standard comfortable internal temperature. This standard reference temperature equates to an external temperature of 15.5°C. Every 1°C below this reference equates to one degree-day, therefore if an average temperature of a particular day is 9°C this day would have 6.5 degree-days. Degree-days can then be aggregated to give a total number per year for a particular area and used to compare the relative annual energy required for heating.

In this study only the system efficiency was consistently calculated across all sites and both monitoring periods, therefore only the system efficiency can be temperature-corrected for every site. In order to calculate a temperature-corrected system efficiency, both the electricity consumption (electricity to the heat pump including any auxiliary and immersion) and heat use (space heating and domestic hot water to the taps) must be temperature-corrected first.

Monthly measured electricity consumption and heat supplied were plotted against the number of monthly measured degree days for each site and each monitoring phase. An example of this plot is illustrated in Figure 78.

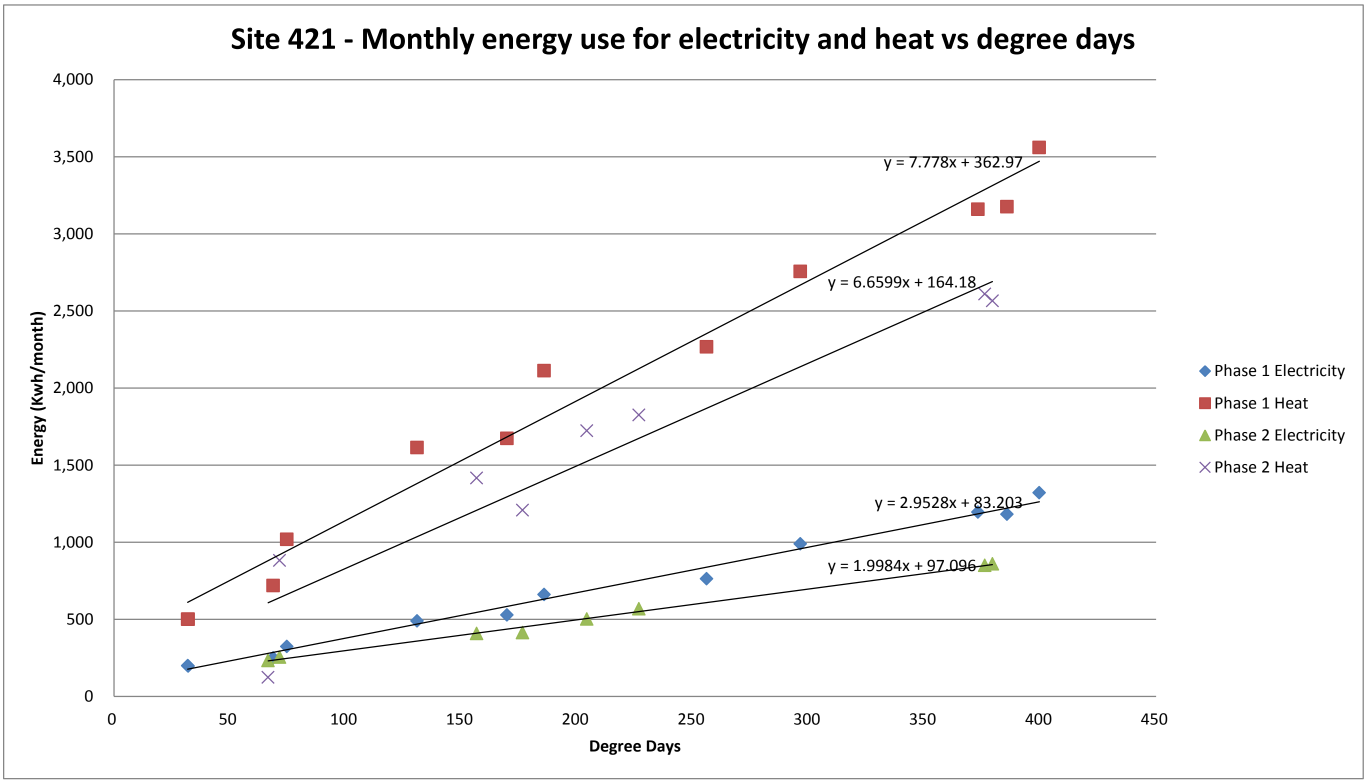

Figure 78: Monthly electricity and heat use plotted against monthly degree days for site 421.

The line of best fit provides the monthly average energy use per degree day. In order to normalise the data, a 20 year average number of degree days (from 1987 to 2006) for the closest weather station for each site was chosen. This average was applied to the equation of the line of best fit with the intercept multiplied by 12 to give an annual, normalised, temperature corrected figure for both electricity consumption and heat use for each site. The corrected heat use is then be divided by the corrected electricity consumption to give a temperature-corrected system efficiency.

Correlations between electricity consumed and degree days and heat generated and degree days were found to be good, with only eight correlations out of 164 having regression coefficients, R2, ≤0.8. Table 40 shows the results.

	Phase I		Phase II	
	R^2 Electricity vs. degree days	R^2 heat vs. degree days	R^2 electricity vs. degree days	R^2 heat vs. degree days
R^2>0.8	37	36	41	42
R^2<=0.8	1	2	3	2
Total	38	38	44	44

Table 40: Regression coefficients for scatterplots of electricity consumption and heat generation as a function of degree days

15. Appendix E: Sizing of heat pumps

Section 4.2.1 of MCS MIS 3005 Issue 3.1 describes the procedure for sizing heat pumps correctly, stating that "A heat loss calculation should be performed on the building using a method that complies with BS EN 12831".

For the sites in the trial, heat loss coefficients have been calculated according to two methodologies:

a) Using SAP
b) From measured daily average heat power and the daily average difference between internal and external temperatures during the heating season.

Neither of these methodologies is compliant with BS EN 12831 but the second method would be expected to give the most accurate results.

Figure 79 shows a comparison of the results of these two methodologies, for houses in both phases. The straight line represents a one to one fit. It can be seen that the SAP estimates of heat loss coefficients are higher, on average, than the measured ones. There are a handful of estimates, particularly for the larger houses (floor area from 180m^2 to 480m^2) for which the SAP estimates are very much higher than the measured heat losses; it is possible that not all of the house is being heated. Furthermore, the SAP heat loss coefficients refer to the fabric only, while the measured heat loss coefficients take account of internal and solar gains.

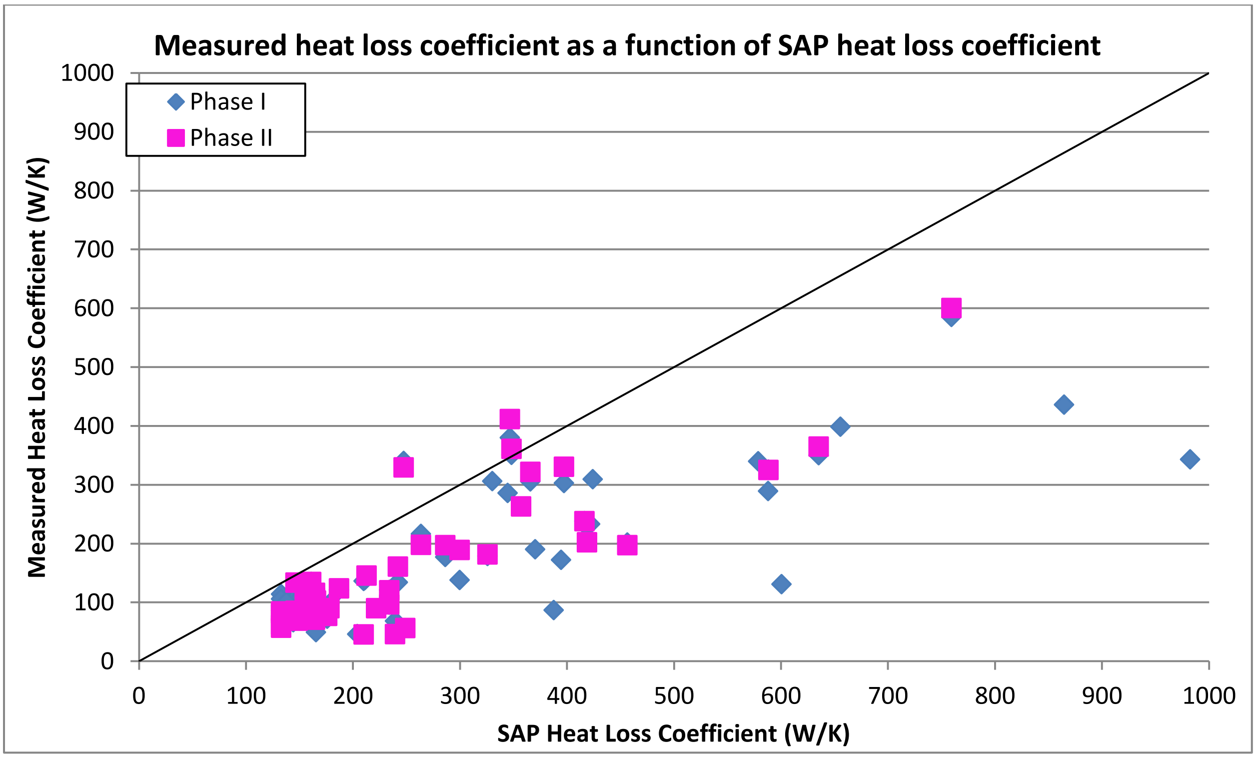

Figure 79: Comparison of measured heat loss coefficients and SAP heat loss coefficients

Based on measured heat loss coefficients, seven sites were under-sized in Phase I and three were under-sized in Phase II. Under-sizing would be expected to affect the SPF_{H4} as auxiliary electricity would be required in cold weather. However, the winter of 2010-11 was mild and there were only a few days for which the average daily temperature was < 0˚C at these sites, so this effect has not been seen in the data.

16. Appendix F: Comparisons with SAP

Full SAP calculations were carried out on almost all of the properties within phase II. SAP calculates the annual space and water heating requirement of a building based on the occupancy, building fabric and the building services installed.

The measured space heating demand can then be compared with the space heating requirement that SAP predicts. This is illustrated in Figure 80. This provides a representation of how well SAP predicts the space heating requirement for a selection of different houses with heat pumps. On average, SAP predicts space heating well, even though the heat loss is under-estimated (see Figure 79). This is likely to be because SAP assumes a bimodal heating pattern whilst many of the heat pump houses were heated continuously. Furthermore, unlike the chart of heat loss coefficients Figure 79, both axes in Figure 80 take account of internal and solar gains.

Other reasons for the discrepancy between Figure 79 and Figure 80 might include householders heating their houses to higher temperatures and differences between the SAP assumptions regarding degree days and the actual degree-days during the field trial periods.

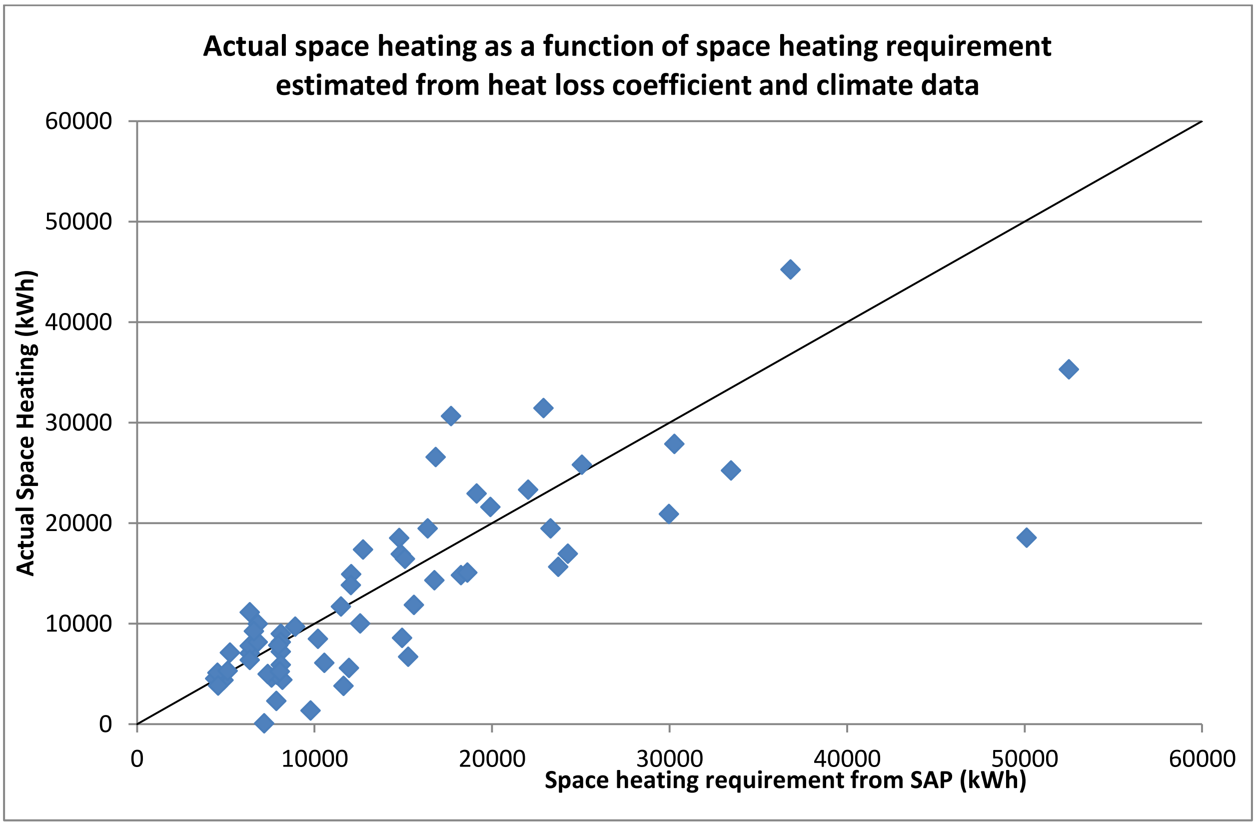

Figure 80: Comparison of measured annual space heating demand with SAP estimates for Phase II sites