Programme Area: Distributed Energy

Project: Micro DE

Title: Heat Meter Investigation

Abstract:

Please note this report was produced in 2010/2011 and its contents may be out of date. This deliverable is an additional output from the Micro-DE project, commissioned to review the current performance capabilities of different heat meters available in the UK. Four different technologies of heat meter were trialled at 8 different sites on heating systems including traditional boilers, heat pumps, solar thermal systems and an electric water heater. The report highlights the importance of correct installation techniques on accuracy of readings. The report also states that significant errors in accuracy are likely when measuring domestic hot water consumption due to rapidly changing flow rates, errors of up to 20% between meters were recorded.

Context:

The project was a scoping and feasibility study to identify opportunities for micro-generation storage and control technology development at an individual dwelling level in the UK. The study investigated the potential for reducing energy consumption and CO_2 emissions through Distributed Energy (DE) technologies. This was achieved through the development of a segmented model of the UK housing stock supplemented with detailed, real-time supply and demand energy-usage gathered from field trials of micro distributed generation and storage technology in conjunction with building control systems. The outputs of this project now feed into the Smart Systems and Heat programme.

Heat Meter Investigation

Final Report

October 2011

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Revision History

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26th July 2011	0.2	EC	Pictures & captions inserted, draft completed
27th July 2011	0.3	EC	Including comments from TS, PR, FH, NW, MP
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Detailed changes since Preliminary Report v1.0

Executive Summary: Updated.

Section 2:

- Added description of second compact heat meter.
- Added description of second non-invasive flow meter (Micronics).

Section 3:

- Added section on validating Passiv temperature sensors.
- *Newbury test rig*: added results with sensors lagged, second compact heat meter, and with Grundfos calibrated; updated discussion.
- *Legacy boiler*: added results with sensors lagged; updated discussion.
- *Ground source heat pump*: added results and discussion (previously no results), including disaggregated COP.
- *Solar thermal*: corrected for Grundfos misconfiguration.
- *Non-invasive flow meters*: moved Solenvis results to this new section, results of three installs of Micronics added including boiler efficiency calculation.

Conclusions: Updated.

Contents

Executive Summary

Heat metering is the only feasible way to measure the efficiency of a heat pump, or indeed any other water-based heating system, but heat meters are often expensive and difficult to read. With the Renewable Heat Incentive (RHI) arriving next year, it is important to understand the feasibility of widespread installation of heat meters for fiscal metering. In addition, measuring heat pump efficiencies will guide their installation and configuration, which can be notoriously difficult. The ETI has commissioned PassivSystems to investigate real-world monitoring of heat pumps using heat meters, and this report contains the final output from this investigation.

Four different technologies of heat meter were included in the investigation: standards-approved compact heat meters (two models), PassivSystems prototype heat meters, new heat metering technology from Grundfos, and non-invasive heat meters (two models) that require no plumbing work. These devices were trialled at eight different sites, including two fossil-fuel boilers, an electric water heater and a solar thermal system, in addition to four heat pumps. This provides a broad scope while still being relevant to the key interest in heat metering of heat pumps.

The investigation has shown that the Passiv and Grundfos heat meters can give good long-term performance with less than 4% error in comparison with a standards-approved compact heat meter. The Micronics Portaflow 330 non-invasive flow meter performed well (generally less than 4% error), but the Solenvis SL2 recorded such an inaccurate flow rate (a factor of two out) that is not useful for domestic applications.

Proper physical installation of heat meters is important, particularly for the temperature probes: inaccuracies in measuring the temperature of the heat-carrying fluid can cause large errors in the metered heat transfer when the flow-return temperature difference is small, as is often the case for heat pumps. If non-invasive temperature sensors are used in this scenario, it is very important to ensure good thermal contact to the pipe and sufficient insulation between the sensors and ambient air.

Heat metering of domestic hot water consumption is likely to be inaccurate, due to the rapidly changing flow rates and temperatures involved; our investigation showed inconsistencies of 10-20% between meters, although this may be partly due to differing thermal contact.

PassivSystems' remote monitoring permitted continuous, reliable data collection and flexible back-end processing, all important for investigations such as this one. The separate flow and temperature measurements recorded by the Passiv heat meter are valuable for diagnostics, consumption analysis, and eventually, efficient heat pump control.

In conclusion, properly-installed heat meters can provide sufficiently accurate and reliable information for heat incentive schemes or community heating projects, and remote monitoring can eliminate the need for manual meter reads. A non-invasive heat meter, whilst far too expensive for widespread deployment, provides a feasible alternative for temporary installs or one-off efficiency measurements.

1. Introduction

It is essential to be able to measure the heat that is actually produced by a heat pump, for example to determine its efficiency. For water-based systems, this is typically done with a *heat meter*, which measures heat according the the temperature change in each unit of water that passes through the heat pump. Heat metering devices are not always satisfactory: they can be expensive, difficult to set up properly, and hard to monitor. In this project, several heat metering methods are investigated and compared, and conclusions are drawn as to their accuracy, reliability, and real-world utilisation. The same heat metering technology can be applied to any water-based heating system; this investigation also incorporates the application of heat meters to a variety of heating systems such as a fossil-fuel boiler and a solar thermal system.

Heating systems are usually metered according to the energy *input*, for example a gas meter or a electricity meter, but the quantity that actually matters to the consumer is the heat *output* actually delivered by the system, to heat a house or provide hot water etc. Comparing the heat output to the energy input enables the efficiency of system to be measured. This is useful for a fossil-fuel boiler, to determine if it needs replacing for example, but is particularly important for heat pumps, whose efficiency (and thus financial viability) depends strongly on how they are installed, configured, and controlled. In the UK, the real-world efficiency of heat pumps is often significantly lower than expected – hence measuring their heat output is very important. Without this knowledge, home owners could be running an inefficient system for years and be unable to pinpoint the cause of high energy bills.

A secondary driver for this investigation is the UK Government's Renewable Heat Incentive (RHI), which aims to encourage take-up of renewable heating technology by paying consumers according to the amount of renewable heat they generate, through a heat pump for example. The tariff will be either deemed (according to the nominal system capacity), or metered – and in the latter scenario a heat meter would be required. Hence there is likely to be a very widespread requirement for an affordable heat meter, that is easy to read and process remotely. A related application is when consumers are charged according to the amount of heat they consume, for example in a community heating scheme.

This investigation includes four different heat metering technologies:

- **Compact heat meter**: a standards-approved self-contained off-the-shelf heat meter. Two meters are included in this trial, Integral V-Maxx and NZR/Syxthsense WZCD;
- **Passiv heat meter**: PassivSystems' prototype heat meter, consisting of a water meter plus existing Passiv pipe temperature sensors, with heat calculations carried out as a post-processing step;
- **Grundfos heat meter**: a heat meter based on the Grundfos VFS, a modern low-cost technology for measuring flow with no moving parts, with Grundfos temperature sensors, and a separate heat calculator;
- **Non-invasive heat meter**: heat metering using an ultrasonic flow meter that requires no plumbing, together with separate temperature sensors and heat calculator. Two meters are included in this trial, Solenvis SL2 and Micronics Portaflow 330.

The main aim is to compare the accuracy and reliability of these four technologies. All of these are capable (via an impulse output) of remote logging and monitoring in conjunction with PassivSystems equipment – a significant benefit for future tariff processing for RHI schemes.

Heat meters have been trialled in eight different properties with the following heating systems:

- Heat pumps (four properties, two air-source and two ground-source)
- Solar thermal
- Oil- and gas-fired boilers
- Electric hot water heater

The original aim for the project was to concentrate on heat pumps, but the scope has been extended to incorporate these other types of heat source in order to check their accuracy under different loads; the results are still applicable to heat metering of heat pumps.

Section 2 describes in more detail each of the heat metering technologies, their expected performance and limitations, and some findings on their real-world usage. Section 3 describes in more detail our results from each site together with analysis, and overall conclusions are drawn in Section 4.

2. Heat meters

This section provides a brief introduction to heat metering and the heat meters included in this investigation. The subsections below cover legislative approval standards for heat meters, details of the four heat meters included in this investigation, and a comparison table of technical parameters.

Within the context of this investigation, heat metering involves measuring the net heat produced by a heating system by monitoring the properties of a heat-carrying fluid (e.g. water or a water-glycol mixture). Firstly, the volume flow rate of the fluid through the heating system is measured (e.g. litres per second). Secondly, the temperature difference between the fluid leaving the heating system ("flow temperature") and returning to the heating system ("return temperature") is measured.

The *volumetric heat capacity* of the fluid is the amount of energy required to heat one unit volume (e.g. one litre) of the fluid by one degree, and so multiplying this figure by the volume flow rate and by the temperature delta gives the power output of the heating system: the energy provided per second by raising a volume of water through a temperature difference. Integrating this power output over time gives the total heat energy produced by the system. The dependence on heat capacity is an important subtlety, as heat transfer fluids can include glycol (for example, if heat pump or solar thermal pipework passes outside), which will reduce the heat capacity from that of pure water.

Each of the heat meters listed below incorporates *(a)* a flow meter, which measures the volume of liquid flowing through it, *(b)* temperature sensors on the flow and return fluid, and *(c)* a method of calculating heat from these measurements.

2.1 Heat meter standards

The European Union Measuring Instruments Directive (MID) specifies standards for water meters and heat meters.[1] These are briefly described below with regard to the accuracy specifications; in this investigation meters will be compared with reference to these figures. Note that the English EN1434 standards impose the same accuracy standards as the MID standards.

The MID standard for **water meters** specifies a maximum permissible relative error (MPE) for water volume of 2% (for water below 30°C) or 3% (for water above 30°C). It also permits a 5% MPE for flow rates between the specified minimum flow rate and a "transitional flow rate."

The MID standard for heat meters species an MPE which is the sum of the error from the three parts of the calculation (flow, temperature difference, and the heat calculation itself). There are three classes for flow accuracy; broadly Class 1 = 1%, Class 2 = 2%, and Class 3 = 3%, but there is also allowance for greater error at lower flows depending on the dynamic range of the device (but never more than 5% error).

For temperature difference, the accuracy required is a function of the temperature difference, and varies from 3.5% at the specified minimum temperature difference down to

0.5% at high temperature differences (exact specification [percentage]: $0.5 + 3\Delta\theta_{\min}/\Delta\theta$). For the heat calculation itself, the same applies but with a maximum of 1.5% (exact specification [percentage]: $0.5 + \Delta\theta_{\min}/\Delta\theta$).

These mean that we can determine the maximum expected error of a MID-approved heat meter in a particular experimental scenario, and also assess the capability of a heat meter against the MID standard.

2.2 Compact heat meter

A key aim of this investigation is to compare heat metering methods against a standards-approved, known good quality heat meter. The Integral-V MaXX [2] (Figure 1 below) was identified as a cost-effective heat meter that is MID-approved (Class 2). It is manufactured by iTron and supplied in the UK by MWA Technology. The meter is plumbed in, and has a turbine for flow rate measurements and two PT100 temperature probes for temperature measurements. One of these is inserted into its body (for direct fluid contact), and the other is mounted to measure the temperature of the opposite flow. Within these experiments, this sensor was attached to the outside of the pipe, with measures taken to ensure good thermal contact.

The PT100 sensors have a two-wire connection, which can only give 0.3° accuracy at best, but to meet the EN1434 heat metering standards the two sensors are *paired* during the production process at three different temperatures. This means that the absolute temperatures provided by the sensors can be up to 2° out from the true temperature, but the temperature delta (which is important for heat metering) will be accurate.

A variety of flow rate models are available; the 2.5m^3/h model was chosen conservatively, but does not have the best sensitivity at low flow rate (e.g. the 0.6m^3/h model has a minimum flow rate of 6L/h, vs 25L/h for the 2.5m^3/h model).

The meter has an impulse output option which provides two outputs, for volume (one pulse per 10L) and heat (one pulse per kWh). These impulse outputs are connected to a Passiv WSC (see below).

In addition, a second model of compact heat meter (Syxthsense WZCD [4]) was included in the investigation, as it was incidentally available in two of the install locations. This meter, supplied in the UK by Syxthsense (WZCD-M-BUS-2-5-D) but manufactured by NZR, is quite similar to the Integral-V MaXX. It has a maximum flow rate of 2.5m^3/h and is compliant to EN1434; the only notable difference is that it has PT500 temperature sensors rather than PT100 (and so is nominally more accurate). In both properties it is connected to a third-party system via M-Bus to log flow and temperature readings (with cumulative volume only available in m^3, but flow rate logged in litres per hour).

Figure 1: iTron Integral-V MaXX compact heat meter. The red temperature probe is inserted into the opposite pipe. Photograph from Ref. [2].

Figure 2: Syxthsense/NZR WZCD compact heat meter. The red temperature probe is inserted into the opposite pipe. Photograph from Ref. [4].

2.3 Passiv heat meter

PassivSystems have a prototype heat meter that consists of a water meter plus Passiv pipe temperature sensors (Figure 3). Together with other Passiv equipment, this provides a flexible remote heat metering solution: volume flow and temperature measurements are recorded on a Passiv server, from where they can be checked and processed anywhere with an internet connection.

The heat meter forms part of PassivSystems' heat pump monitoring solution; together with an electricity meter, the COP of a heat pump can be calculated, and room temperature sensors complete the picture of the heat pump's performance.

The water meter in Figure 3 is an NZR Modularis supplied by Syxthsense (WZW-M-2-5 DN20 Modular Hot Water Meter [5]). Similarly to the Integral-V, the 2.5m^3/h model was chosen, but there are lower flow rate alternatives available as well. The meter has a impulse output which is connected to a modified PassivSystems Wired Sensor Communicator (WSC) [6], whose firmware detects and counts the pulses and transmits the cumulative count at a configurable reporting interval (typically 15 to 60 seconds). The water meter is not officially standards-approved but its datasheet shows flow measurement performance better than 2%, thus meeting the accuracy criterion for MID approval.

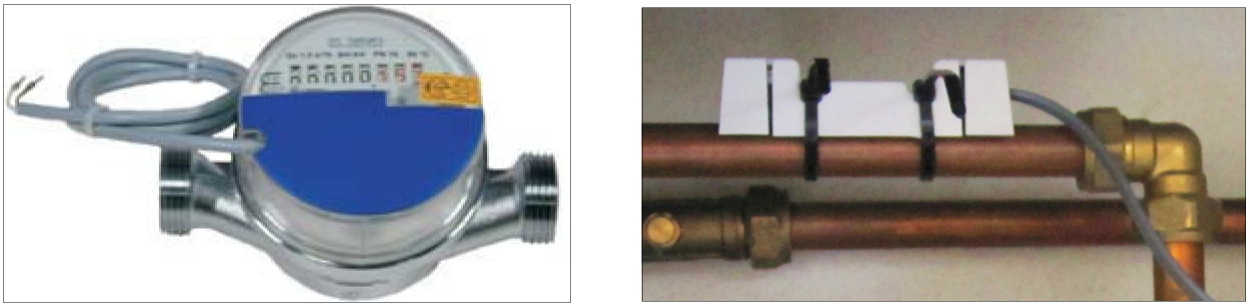


Figure 3: Passiv heat meter: Syxthsense water meter[5] (left) and Passiv pipe temperature sensor (right).

Temperature sensing is provided by a Passiv pipe temperature sensor, consisting of a compensated thermistor connected to the outside of the pipe via thermal pads, and connected to the WSC via an I^2C bus. The Passiv system logs temperature readings separately from flow and thus permits more detailed analysis into heat transfer and heat pump performance than a standalone heat meter. The reporting rate is configurable but typically 15 seconds is used so that rapid temperature changes can be captured.

The temperature sensors, being non-invasive, are easy to install, but can suffer from incomplete thermal contact with the heat-carrying fluid and record a temperature closer to ambient. This can give, empirically, an error of up to 1°C, whereas the sensors themselves are capable of 0.2°C accuracy. Validation of these sensors was carried – see Section 3.1.

The heat calculation is carried out by back-end post-processing. For each pulse, the flow and return temperatures are linearly interpolated from the available readings, and the resulting temperature differences accumulated and multiplied by a volumetric heat capacity. A figure of 4179.6 J/L/K for pure water at 25°C is used[1]; this will underestimate heat slightly at higher temperatures (up to 1% at 100°C). Other methods of calculation are also used comparatively, such as averaging the temperature over the last litre for slow, constant flow rates.

2.4 Grundfos heat meter

The third heat meter included in this trial is based on the Grundfos VFS (Vortex Flow Sensor) [7], a recently developed technology for measuring flow. Together with a Grundfos RPS [8] in the opposite pipe (see Figure 4 below), these can form a heat meter as both devices provide temperature measurements. In this investigation, we utilise an HMDII heat meter display unit [9] [10], which interprets the Grundfos sensor measurements and carries out the heat calculation (see Figure 4 below).

The VFS measures flow by looking at the rate of vortex-shedding from a carefully-proportioned obstacle in the flow. The vortices are counted with a pressure sensor, and this provides a measurement of flow rate. The attractive features are that the sensor has no moving parts and can be produced at low cost (target price point £25 [11]), and that the VFS incorporates a temperature sensor. The RPS measures pressure and temperature, and this temperature measurement forms the opposite half of the heat meter.

For this investigation, the exact models used are the VFS 1-12 L/m and the RPS 0-4 bar. The VFS and RPS natively produce flow and measurements as an analogue voltage between 0.5 and 3.5 volts, or as an RS232 digital interface on top of these signals. The heat calculator unit (HMDII) interprets the analogue signals and provides a heat pulse output (one per kWh) [10] to the Passiv WSC. In this configuration the raw flow and temperature measurements are not available (although the configuration with a Steca controller used for the solar thermal house in Section 3.6 does enable logging of these values). A future configuration of the Grundfos heat meter would not require the HMD: for example, Passiv could interface directly to the VFS and RFS and carry out the heat calculation at the back end.

The Grundfos sensors are not yet certified but are undergoing the approval process [11]. The manufacturer is confident of achieving Class 3, and believes that Class 2 would be possible. This means an expected flow measurement accuracy of 2%-3%.

We understand [12] that the temperature sensors individually have a maximum error of 1°, but this can be reduced through the calibration process (see below) so that the error of the *pair* (i.e. measuring temperature difference) is less than 1°.

1 Except for the long-term monitored air-source heat pump (Section 3.5) and the solar thermal system (Section 3.6): these have a heat-carrying fluid with approx 30% glycol, for which we use a volumetric heat capacity of 3931J/L/K (6% different).

The Grundfos has two subtleties in its set-up:

- **Grounding.** The DC circuitry of the VFS sensor needs to be grounded to the heat-carrying fluid otherwise it reports a high flow rate when there is actually no flow. The sensors, as provided by the manufacturer, do not easily allow for this connection; for this investigation it was required to ground one of the connections in the HMDII to the pipework with an additional wire. All the data included in this report has this ground in place.
- **Calibration.** The temperature sensors in the VFS and RPS need to be calibrated against each other by pressing a button on the HMDII display when the temperature at both is the same. Calibration was possible for one of the two installations within this investigation.

Figure 4: Grundfos heat meter, showing from left to right the HMD, VFS and RPS. Picture taken from Ref. [9]

2.5 Comparison table

	Compact heat meter (Integral-V MaXX) [2]	Compact heat meter (Syxthsense WZCD) [4]	Passiv heat meter	Grundfos heat meter
Volume measurement	(built in)	(built in)	Syxthsense [5]	VFS 1-12 [7]
Starting flow rate (L/h)	5	18	15	
Minimum flow rate (L/h)	25	70	50	60
Transitional flow rate (L/h)	150	280	150	
Maximum flow rate (L/h)	2500	2500	2500	720
Overload flow rate (L/h)	3750	5000	5000	
Accuracy	MID Class 2= 2%		<2%	"1.5% / 5% FS (typical 3 %)"
Flow outputs (used here)	One pulse = 10L	M-bus	One pulse = 1L	None
Heat measurement	(built in)	(built in)	Passiv back-end calculation	RPS 0-4 [8] + HMDII [9]
Temperature sensors	PT100, two-wire, paired	PT500, two-wire, ?paired	Passiv	Grundfos
Minimum temp. difference	3°C	2°C		
Temperature accuracy	ΔT: < 3.5% (EN1434)	ΔT: < 3.5% (EN1434)	±0.1° (perfect thermal contact)	±1°, 1.5% FS; ΔT (calibrated): < 1°
Heat outputs (used here)	One pulse = 1kWh	M-bus (EN1434-3/4)		One pulse = 1kWh (via HMDII)

2.6 Non-invasive heat meter

All of the heat meters above require plumbing work to install the flow meter that measures the volume flow rate of the heat-carrying medium. An extremely attractive alternative is a *non-invasive flow meter* that can be simply mounted on the outside of a suitable piece of the pipe work. Such devices use ultrasonic technology, and deduce the flow rate from the difference in transit time each way between a pair of ultrasonic transducers.

The disadvantage of a non-invasive ultrasonic flow meter is that it is very expensive (>£2000), but it is easy to conceive of a scenario where the efficiency of a heating system is characterised with a short-term loan (e.g. one day or one week) of a non-invasive flow meter; if the meter is used to characterise multiple properties it would quickly become economic. Also, many heating systems have a constant flow rate as they have a fixed power circulation pump, so the flow rate could be characterised as a one-off.[2]

Setting up a non-invasive flow meter is not trivial. There needs to be a good ultrasonic impedance match between the transducers and the fluid (usually achieved with a grease), and the meter must be configured with the pipe diameter, the fluid type (as this affects the speed of sound), and the shape of bounce to use (e.g. a "W"-shaped bounce is used for smaller pipe diameters). This difficulty is somewhat offset by the inclusion of a quality measure on the meter's display that indicates how well the ultrasonic signals are transmitted and received.

Two different non-invasive flow meters were included in this investigation: the Solenvis SL2 and the Micronics Portaflow 330.

The **Solenvis SL2** handheld flow meter [13] [14] is shown in Figure 5 below. The data sheet [13] claims that its flow measurement accuracy is 1-2% for flow speeds above 0.5m/s. The flow meter can be used together with SVN F22 heat calculator [15] as a heat meter (see Figure 5 again); the F22 receives an impulse output from the SL2 every litre, and measures temperature with two PT100 probes, and provides a heat calculation via a display or an impulse output. For this investigation the devices were hired for a two-week period, with an option to purchase; in the end PassivSystems were not satisfied with the performance (see results below) and decided not to purchase the unit.

The **Micronics Portaflow 330** is a similar device. The Technical Data Sheet [16] quotes the flow measurement accuracy is ±3% for flows of above 0.2m/s for domestic-sized pipes. The Portaflow 330 supports an impulse output, so flow can be remotely monitored using a connection to a Passiv WSC, and it can be used as a heat meter in conjunction with Passiv temperature sensors (or alternatively with a unit such as the F22 and PT100 probes in the same way as the Solenvis). The device was for a one-week period for this investigation.

2 This will not be true if there are thermostatic radiator valves, but these could be set to fully open during the assessment period, for example. It would also change if components of the heating system degraded in time.

Figure 5: Left: Solenvis SL2 non-invasive flow meter handheld unit.[13] Right: SVN F22 heat calculator.[15]

Figure 6: Micronics Portaflow 330 non-invasive flow meter. [16]

3. Results

3.1 Validation of Passiv temperature sensors

In order to verify the accuracy of the Passiv heat meter, two experiments were carried out to validate temperature readings reported by the Passiv pipe temperature sensors. These experiments utilised a PTP381 Paterson Colour Thermometer[17] which is accurate to 0.14°C (achieved by manually reading a scale to 0.25°F).

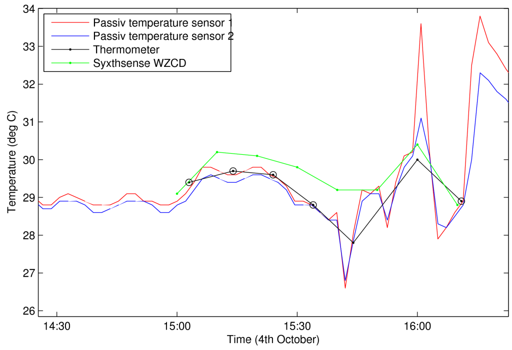
Immersion test. The first experiment involved immersing two Passiv temperature sensors and the thermometer in three heat baths at different temperatures, using a plastic bag to protect the sensors from water. Air was removed from the bag, and the sensors were left for 30 minutes to equilibrate with the heat bath. The results are shown in the table below.

Heat bath	Passiv pipe temperature sensor 1	Passiv pipe temperature sensor 2	Paterson thermometer
Hot tub	35.2°C	35.0°C	35.3°C
Swimming pool	25.0°C	24.9°C	25.0°C
Fish tank	24.6°C	24.5°C	24.1°C
RMS error	*±0.29°*	*±0.29°*	

Solar thermal test. For the second experiment the Passiv temperature sensors were installed on pipes from a solar thermal system, as was a sensor pocket in the pipework modified to have the Paterson thermometer inserted. A Syxthsense WZCD heat meter was available on the same pipe with a temperature output from a PT500 sensor. A graph of the temperature readings from two hour-long periods on successive days is shown in Figure 7.

Solar thermal systems exhibit rapid changes in flow temperature, for example when the sun comes out, and at these times it is hard to compare synchronous temperatures. Selecting only the points when temperatures were fairly static (circled in Figure 7), temperature sensor 1 has an RMS error of 0.13° and temperature sensor 2 has an RMS error of 0.28°.

The RMS difference between the two Passiv sensors was 0.2°. One of these was uninsulated (although has a plastic cover), and the second had lagging added.



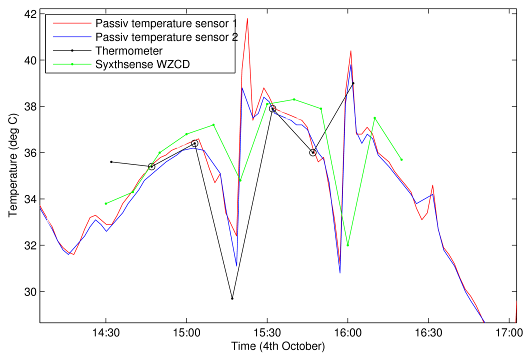


Figure 7: Graphs of comparative temperatures on a solar thermal return pipe for periods on two different days (left and right). Circled points are manually identified reliable points for comparison, when temperatures are not changing rapidly.

Discussion. Good agreement was achieved between the Passiv temperature sensors and the Paterson thermometer, of the order of their respective tolerances, plus a small systematic error due to the effects of ambient temperatures. It is odd that the uninsulated sensor had the higher temperature reading.

The Syxthsense WZCD PT500 has a more significant discrepancy with the Paterson thermometer. We believe this is because of the inherent inaccuracy of an individual PT sensor; this does not necessarily affect the sensor's heat metering accuracy as the two PT500s are likely to be paired.

In summary, the experiments have shown that the Passiv temperature sensors give better than 0.3°C accuracy in a real world scenario.

3.2 Newbury Test Rig

Installations in real houses are representative of real heat consumption, but it can be quite difficult to experiment with configurations of equipment, particularly where plumbing is involved. As an alternative, a flexible test rig has been installed in the Newbury offices of PassivSystems, where meters and sensors can be quickly configured, and easily monitored on site. The rig consists of plumbing loops on the hot and cold sides of an in-line electric water heater, used to provide hot water to the office kitchen. These plumbing loops can be easily isolated for modifications or for operation only during office hours. Figures 8 and 9 below show a schematic diagram and a photograph of the set-up. For part of the investigation, a Syxthsense WZCD compact heat meter was also present in-line with the others, connected to a separate data collection system.

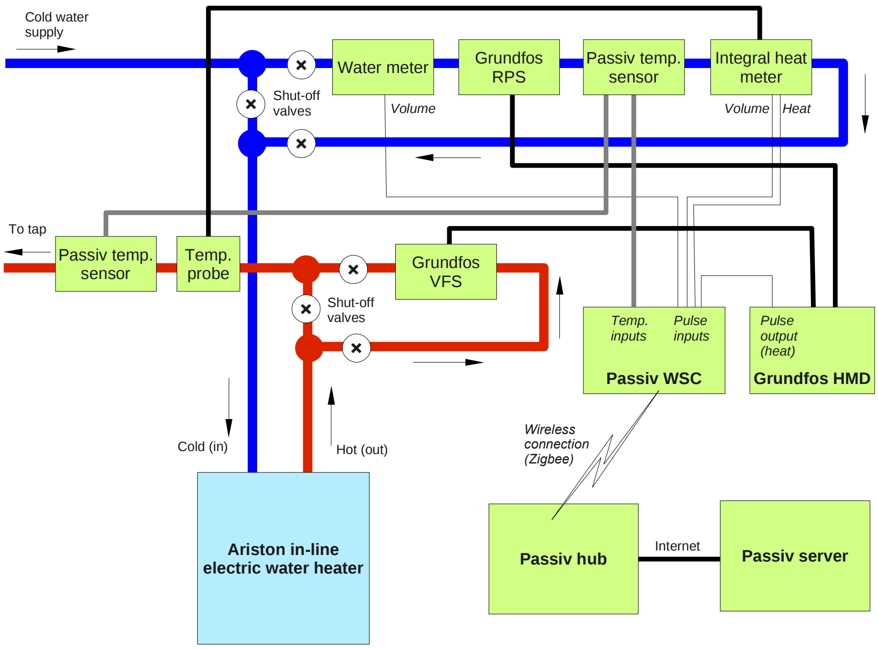


Figure 8: Schematic diagram of heat metering equipment at the Newbury test rig. The heat provided by an in-line electric water heater is measured using sensors on each side (i.e. cold and hot sides). Shut off valves are installed so that the test rig can be easily isolated for modifications.

Figure 9: Photograph of the Newbury test rig.

Within this investigation, the heat delivered by the electric water heater was measured using four different methods: *(a)* the Integral-V MaXX compact heat meter, *(b)* the Syxthsense WZCD compact heat meter, *(c)* the Passiv heat meter, and *(d)* the Grundfos heat meter. The rig has been installed for four months in total, although the WZCD meter was only available for two weeks of that time.

Pulse counting check. As a verification check on the pulse counting and remote monitoring, the recorded pulse counts were compared with readings made using the displays on the meters. Over a nine day period three of the readings matched exactly (425L through the Syxthsense water meter, and 450L and 13kWh through the Integral-V) and the last was one pulse out (the Grundfos heat meter, which registered 14 pulses but the display incremented from 116kWh to 131kWh = 15kWh). We do not believe this is significant.

Results. The table below shows comparative volume and heat measurements from the meters for five periods of time when different heat meters were installed. Percentage differences are calculated using the Integral-V as a baseline.

Lagging was added around the Passiv pipe temperature sensors and the Integral-V flow temperature sensor at the beginning of August, and the Grundfos temperature sensors were calibrated on 14^{th} September. The maximum flow rate was 5L/min ($0.3m^3/h$); consumption was typically in short bursts with a temperature delta of 20° to 40°. Figure 10 shows a graph of a typical day.

Test	Volume/L			Heat/kWh			
	Water meter	IntegralV	WZCD	Passiv	IntegralV	Grundfos	WZCD
13th June – 9th July *(Percentage difference)*	1096 *(-7%)*	1180		35.1 *(+0.3%)*	35		
With Grundfos 21st June – 9th July *(Percentage difference)*	893 *(-5%)*	940		29.0 *(+7%)*	27	32 *(+19%)*	
Lagging added 5th August – 9th Sept. *(Percentage difference)*	1317 *(-4%)*	1370		41.7 *(+16%)*	36	45 *(+25%)*	
With WZCD 15th August - 2nd Sept. *(Percentage difference)*	625 *(-4%)*	650	646.5 *(-0.5%)*	20.3 *(+16-23%)*	17	22 *(+26-33%)*	12 *(-27-31%)*
Grundfos calibrated 14th Sept. – 11th October *(Percentage difference)*	760 *(-8%)*	830		25.8[3] *(+10-15%)*	23	27 *(+15-20%)*	

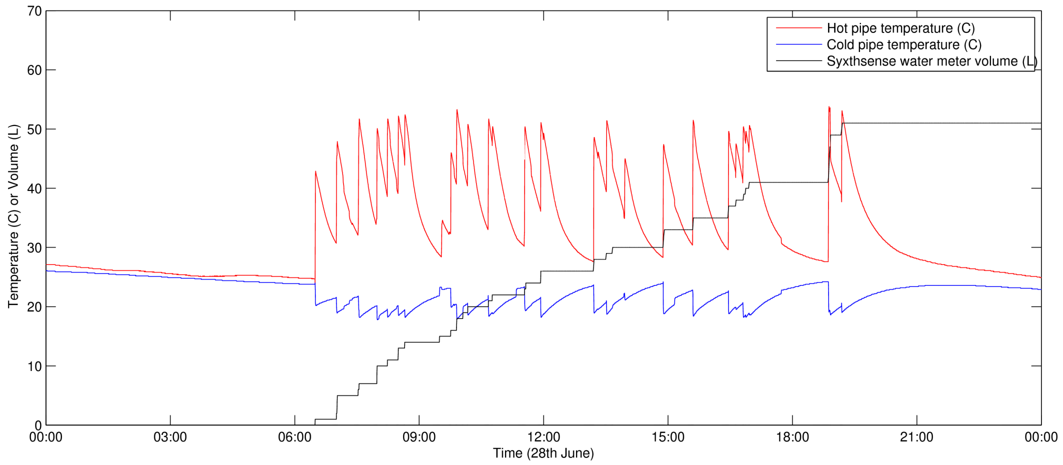


Figure 10: Graph of pipe temperatures and cumulative water volume for one day for the Newbury test rig.

Discussion (volume metering). For flow metering, one would expect an error of up to 5%, since much of the time the meters will be operating below their transitional flow rate of 0.150m^3/h; the discrepancy seen here is slightly higher than this, which is perhaps expected given the highly variable (and low) flow rates for hot water usage in a kitchen sink.

Discussion (heat metering). For heat metering, there are consistent differences between the four heat meters of the order of 20%, with the Passiv and Grundfos heat meters reading higher than the Integral-V. Given the small volume errors (that are in the

3 Including +0.3 kWh estimated correction for one morning disconnected (during Micronics test).

opposite direction), these discrepancies must be due to either the temperature measurements or the heat calculation.

Lagging the sensors makes the discrepancies worse if anything, suggesting perhaps that the Passiv heat meter was in fact under-reading in the earlier periods due to the effect of ambient temperature. Calibrating the Grundfos sensor seems to improves the agreement between the heat meters.

The two standards-approved heat meters have a significant discrepancy, with the second compact heat meter (Syxthsense WZCD) reading 30% lower than the Integral-V compact heat meter. A possible explanation for this is that the flow temperature sensor of the WZCD meter was not lagged, causing it to register lower temperatures and thus less heat.

On the other hand, the Passiv and Grundfos heat meters agree quite well (7% error over the entire period). Both of these might be expected to be inaccurate for hot water consumption measurement: the Passiv heat meter is dependent on 1 litre pulses, and the Grundfos will not measure low flow rates well nor does it have accurate temperature sensors. Unfortunately we do not have the Grundfos volume measurements available to understand whether there is discrepancy within the flow measurement part of the heat calculation, since we just get a 1kWh pulse from the HMDII.   The Grundfos could be overestimating flow (for example, by accumulating volume when there is actually none) and underestimating temperature difference, and still give the same heat output.

Note that for expected heat metering deployment scenarios, such as heat pump monitoring for the RHI, heat will not be delivered in short bursts such as here, but instead circulation pumps run for longer periods during which the heat meters will perform better. The large temperature differences occurring here make the temperature part of the heat calculation more accurate, but the rapid variations in temperature make it harder to establish exactly how much energy is transferred with each litre of water.

For the Passiv heat meter, our view is that it is performing as well as expected, and is comparable to other heat meters. Overall, we conclude that is difficult to meter heat more accurately than ±10-20% for hot water consumption from a tap.

3.3 Fossil-fuel boiler

In order to broaden the study beyond heat metering of domestic heat pumps, we also included a house with a fossil-fuel heating system. A site was identified for the trial; this house has an oil-fired range stove (a Stanley Superstar 60000) which has a single burner used for both heating and cooking. The stove is controlled by a Passiv Hub to provide hot water (to a gravity-fed cylinder), and also produces heat when used for cooking; virtually no space heating was used during the trial period.

Passiv and Integral-V heat meters were installed on the flow and return pipes from the boiler – see Figure 11 below. Four month's data was available for the investigation, and a graph of a typical day is shown in Figure 12 below. An oil flow meter was also installed (independently of this investigation) which would permit boiler efficiency calculations, but unfortunately its pulse output protocol is incompatible with the current monitoring WSC hardware.

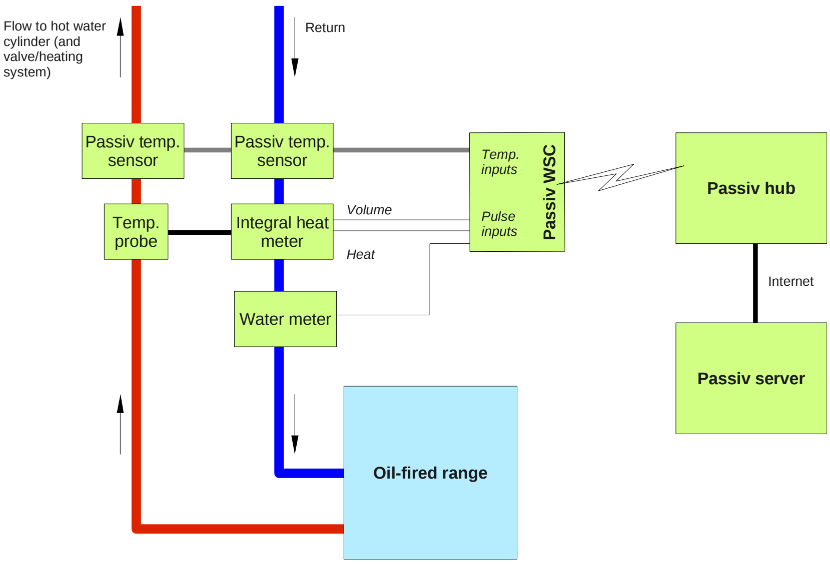


Figure 11: Schematic diagram of heat metering equipment monitoring a domestic oil-fired range stove.

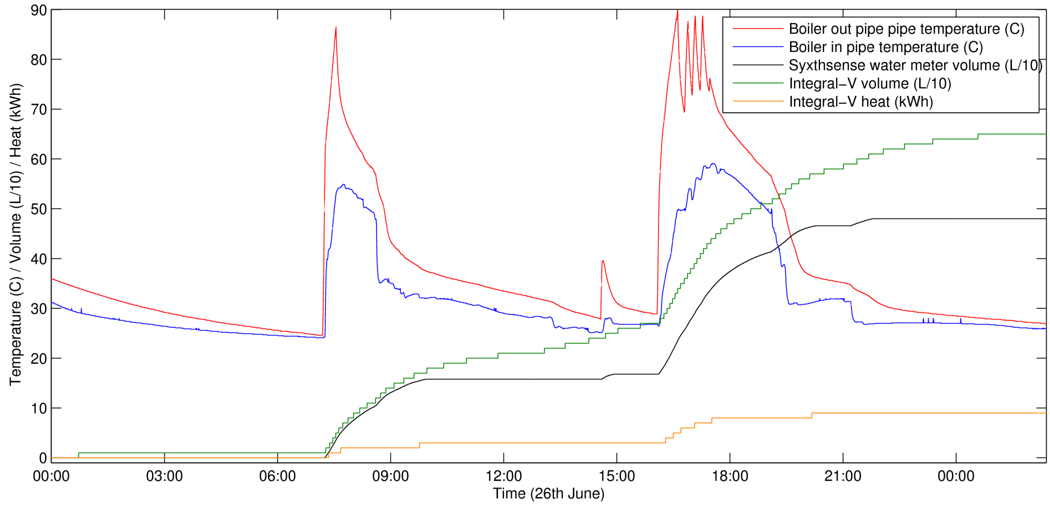


Figure 12: Graph of pipe temperatures, cumulative water volume from both meters, and cumulative heat from the Integral-V for one day for the oil-fired range stove.

Results. The table below shows comparative volume and heat measurements from the meters for two monitoring periods; lagging was added around the pipe temperature sensors on the 22nd July. Percentages differences are calculated as before using the Integral-V as a baseline.

Test	Volume/L (Syxthsense)	Volume/L (Integral-V)	Heat/kWh (Passiv)	Heat/kWh (Integral-V)
10th June – 10th July *(Percentage difference)*	12189 *(-18%)*	14800	297.8 *(+24%)*	240
Lagging added 23rd July – 11th October *(Percentage difference)*	26248 *(-19%)*	32390	604.0 *(+3.8%)*	582

Discussion (volume metering). The volume measures from the two different water meters are significantly different, by nearly 20%. We believe that the cause of this is slow convective flow rates in the gravity-fed hot water system.

From the graph in Figure 12 above, the flow and return pipes have a temperature difference throughout the night, showing continuous flow. The lower flow threshold of the Syxthsense water meter is visible – there is a cusp where it stops recording volume pulses. The Integral-V on the other hand keeps recording pulses on this occasion (although on other days a cusp is apparent also, at a later time).

Quantitatively the Syxthsense water meter stops recording pulses when they are separated by more than roughly four minutes, which equates to a flow rate of 15L/h, well below its specified minimum flow rate of 50L/h. The Integral-V stops recording pulses when they are separated by an hour or more, equating to an approximate flow rate of 10L/h, compared to its (lower) minimum flow rate of 25L/h. Hence this behaviour is expected as both meters are operating out of their specified range.[4]

Discussion (heat metering). The two heat meters show a significant discrepancy for the first period, but agree very well for the second period, during which the pipe temperature sensors were lagged. This is good evidence for the importance of lagging non-invasive temperature sensors: during the first period, the flow temperature sensor on the Integral-V did not have adequate thermal contact with the hot pipe and is recording a temperature nearer to the ambient temperature, and thus underestimating heat transfer.

Note that the discrepancies seen for volume metering do not affect these conclusions, as there was very little heat actually transferred during the overnight convective periods: both the flow and the temperature difference were small. For this install, discrepancies in flow and heat are thus largely independent.

In conclusion, this install demonstrates that the Passiv heat meter measures heat as accurately as a standards-approved heat meter.

4 We implemented a correction to the calculations, which excluded pulses outside the regions where the flow is known to be very slow. This correction improved the agreement between the meters, but did not produce a perfect match – probably because the majority of a 10L Integral-V pulse accumulates overnight and then comes through during a valid period.

3.4 Heat pump test rig

The first site chosen for comparative heat metering of a heat pump is at the laboratory facility of a heat pump supplier. Whilst this does not represent typical domestic usage, it does have the flexibility of being able to install and modify monitoring equipment as required. The site has an air-source heat pump which is used to heat (and supply hot water to) an office area, by pumping heat from a warehouse area. Due to the experimental set up of the rig, the circulation pump is running all the time, and the whole rig is powered down when the offices are not in use.

Passiv and Integral-V heat meters were installed on the flow and return pipes from the heat pump (see Figure 13 below); six days' data was available for the investigation, and a graph of a typical day is shown in Figure 14 below.

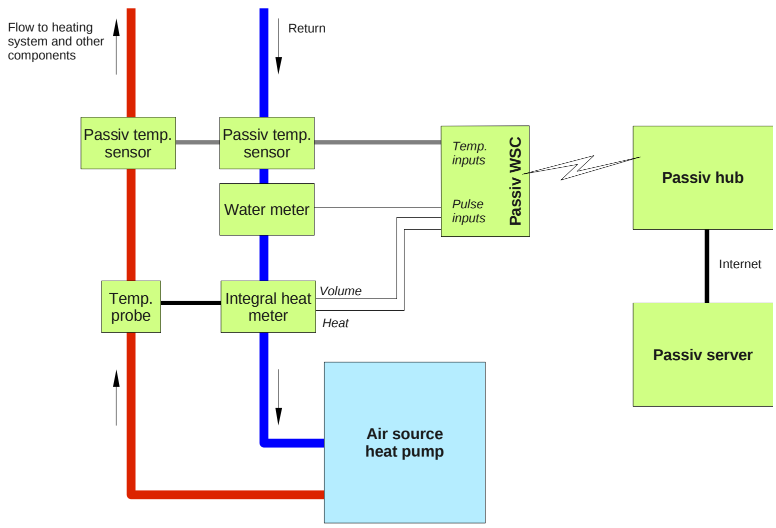


Figure 13: Schematic diagram of heat metering equipment monitoring a air source heat pump in a test rig.

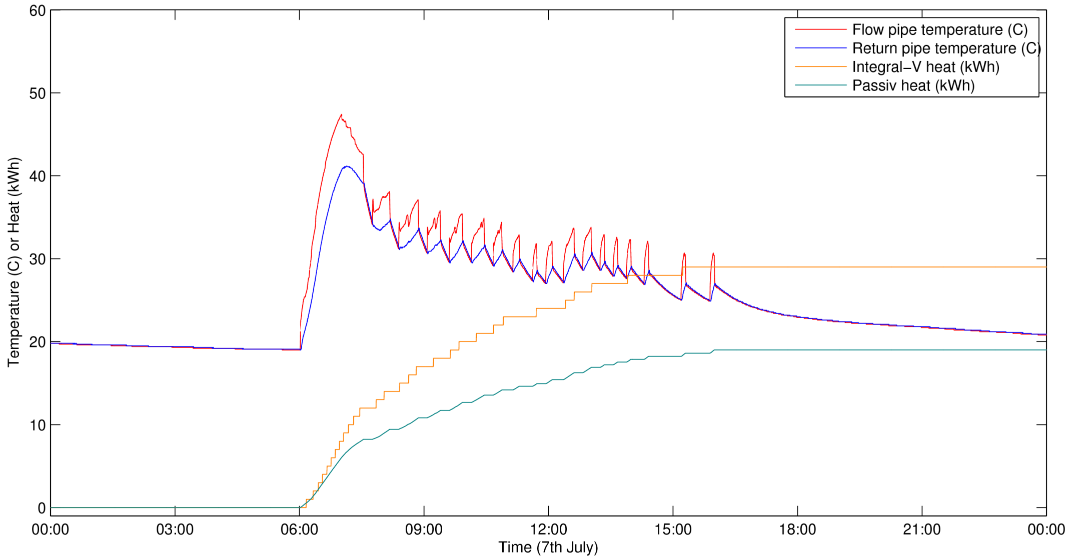


Figure 14: Graph of pipe temperatures and cumulative heat from both heat meters for one day for the heat pump test rig.

Results. The table below shows comparative volume and heat measurements from the meters for the period. The second row shows the result of excluding negative heat transfer from the Passiv heat calculation, and the third is a test of the robustness of the Passiv heat calculation method, by assuming a constant flow rate (see discussion).

Test	Volume/L (Syxthsense)	Volume/L (Integral-V)	Heat/kWh (Passiv)	Heat/kWh (Integral-V)
6th July – 12th July *(Percentage difference)*	122213 *(-0.03%)*	122250	52.1 *(-44%)*	93
6th July – 12th July (excluding periods of negative heat transfer) *(Percentage difference)*			60.3 *(-35%)*	[93]
6th July – 12th July (assuming constant flow rate of 835L/h) *(Percentage difference)*			60.0 *(-35%)*	[93]

Discussion. The two meters have almost perfect agreement on the cumulative water volume in the trial period. The flow rate is very constant, at 835L/h.

The two methods show significant differences (>40%) between their heat readings. This is partly due to the fact that the Integral-V heat meter only measures positive heat. During periods when the circulation pump is running and the heat pump is not, small amounts of heat are transferred in the opposite direction (back from the office space to the warehouse which is cooler). When these are excluded from the Passiv calculation (second row in table), the match improves but there is still a significant difference.

We believe that the underlying cause is discrepancies in the temperature readings; the error remains when a constant flow rate is assumed and the temperatures alone are used to make the Passiv heat calculation (third row in table). Most of the time, the heat pump is producing a flow-return temperature difference of less than 4°C. This means that any inaccuracies in measuring the temperature of the fluid will matter – systematic temperature errors of the order of 1°C are sufficient to explain the discrepancies seen in this trial. Unfortunately it is not possible to log the raw temperature reports used by the Integral-V to confirm this hypothesis.

The Integral-V should have a maximum error in the temperature difference of 3.5% at its minimum temperature difference of 3°C according to the MID specification. The Passiv temperature sensors should be accurate to 0.1°C, giving a very similar error. Therefore we believe that the discrepancy is caused by lack of complete thermal contact between the temperature sensors and the heat carrying fluid.

Additional lagging was added around all temperature sensors to see if improving thermal contact can reduce the discrepancy, but unfortunately the heat pump test rig has been largely out of action, meaning that insufficient data is available to report further.

3.5 Domestic ground-source heat pump

The main target of this investigation is heat metering of heat pumps installed in domestic dwellings. A social housing property was identified that had a ground-source heat pump installed. Figure 15 below shows a schematic diagram of the monitoring system installed at this property. This monitoring enables a full COP (coefficient of performance) calculation to be made for the heat pump, as well as disaggregating delivered heat between space heating and hot water. All pipe temperature sensors were lagged to improve thermal contact with the fluid.

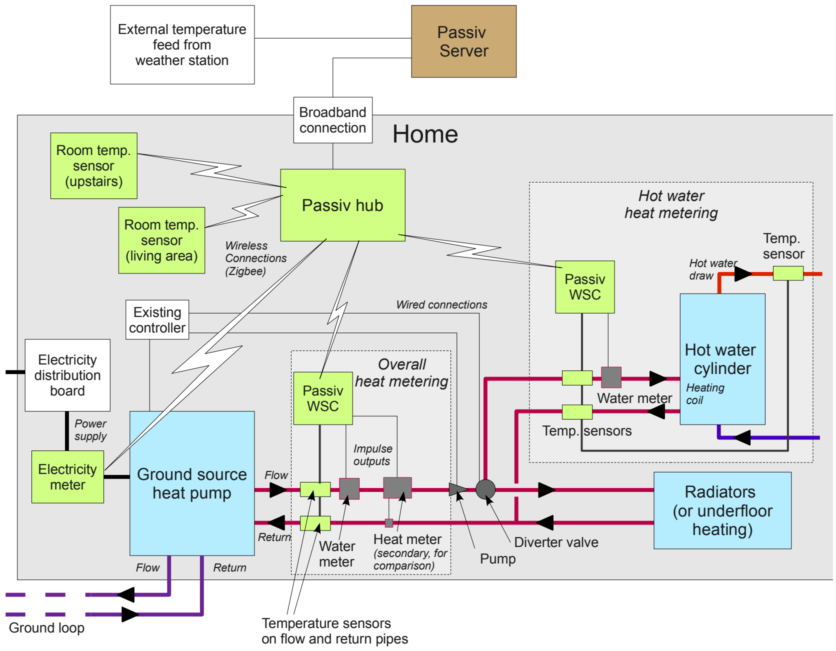


Figure 15: Schematic diagram of the Passiv heat pump monitoring solution for a domestic ground-source heat pump, including two Passiv heat meters and one Integral-V for comparison.

Results (heat metering). The table below shows comparative volume and heat measurements from the meters for two periods. After the first period, the lagging on the flow temperature sensor of the Integral-V was improved.

Test	Volume/L (Syxthsense)	Volume/L (Integral-V)	Heat/kWh (Passiv)	Heat/kWh (Integral-V)
19th August – 5th October *(Percentage difference)*	49377 *(-3.6%)*	51240	404.4 *(+44%)*	281
Improved lagging on Integral-V sensor 5th October – 12th October *(Percentage difference)*	13276 *(-3.7%)*	13780	111.6 *(+14%)*	98

Results (COP). The overall COP (SPF) for the period 18th August to 5th October is 2.36, which can be separated into 2.87 for space heating and 2.01 for hot water.

The table below shows weekly electricity consumption and COP for the monitoring period, together with average external temperature. COP was calculated using the Passiv heat meter. Note that space heating and hot water disaggregation may not be accurate.[5]

Period	COP (overall)	COP (heating)	COP (hot water)	Electricity (heating) /kWh	Electricity (hot water) /kWh	Average external temp. (°C)
19th Aug. – 26th Aug.	2.1	2.66	2	2.58	15.68	14.9
26th Aug. – 2nd Sept.	2.58	2.92	2.06	22.97	15.02	12.7
2nd Sept. – 9th Sept.	2.35	2.85	2.01	10.37	15.37	14.1
9th Sept. – 16th Sept.	2.19	2.9	1.97	4.75	15.38	14.1
16th Sept. – 23rd Sept.	2.51	2.93	2.04	16.32	15.00	12.3
23rd Sept. – 30th Sept.	2.28	2.71	2.03	8.97	15.61	15.1

Discussion. The two heat meters have a significant discrepancy for the first monitoring period, but this is reduced by improvement to the lagging on the Integral-V flow temperature sensors. Nevertheless, the remaining discrepancy of 14% is still concerning.

Since the volume measurements are in good agreement, and flow rates are constant, we believe the discrepancy is due to the accuracy of temperature measurements. The heat pump operates with a typical flow-return temperature delta of 7°, which means that a temperature error of approximately ±0.7° on each sensor would be necessary to explain the discrepancy. This is still greater than the expected tolerances.

We believe that the remaining discrepancy is due to ambient temperature affecting the non-invasive pipe temperature sensors (specifically, the flow temperature sensor on the Integral-V); the dramatic improvement after a minor change to the lagging shows how sensitive the sensors are to these effects.

The COP figures are quite low, and we have been able to identify some installation issues with the heat pump (including that described in footnote 5 below) that we have fed back to the supplier. This illustrates how important it is to remotely monitor the operation and performance of heat pumps, as problems such as these are rarely diagnosed.

5 The calculations in the table are made using the assumption that heat is delivered only to one of hot water and space heating at any time, but the system has a mid-position valve and there is evidence that both operate simultaneously. Hence our calculations are likely to underestimate COP for space heating.

3.6 Long-term heat pump heat metering

The Passiv heat meter has been installed since April 2011 in two homes with heat pumps.

The first home is heated by two ground-source heat pumps. Since the start of April, these have had Passiv full COP (coefficient of performance) monitoring with temperature sensors on flow and return to hot water and the heating system, electricity meters, and water meters. In addition, other pipes have their temperature monitored, and the hot water valve is monitored to determine whether the heat pumps are in hot water or heating mode. The Passiv heat meters have been running continuously for four months without any problems. The total volumes through the two water meters were 630m^3 and 180m^3.

The table below shows the results of our COP calculations, and additionally how much electricity the homeowner is expending on heating and hot water, for four sample days spread through the monitoring period. Figure 16 below shows a typical day's data (at a time when space heating was required).

Ground-source heat pumps **Period**	**COP (overall)**	**COP (heating)**	**COP (hot water)**	**Electricity (heating) /kWh**	**Electricity (hot water) /kWh**
7th April (00:00 to 23:59)	2.86	3.79	1.86	19.7	18.1
10th May (00:00 to 23:59)	2.76	4.25	2.09	4.2	9.3
16th June (00:00 to 23:59)	2.12	-	2.16	0.2	8.9
20th July (00:00 to 23:59)	2.26	-	2.29	0.1	9.7

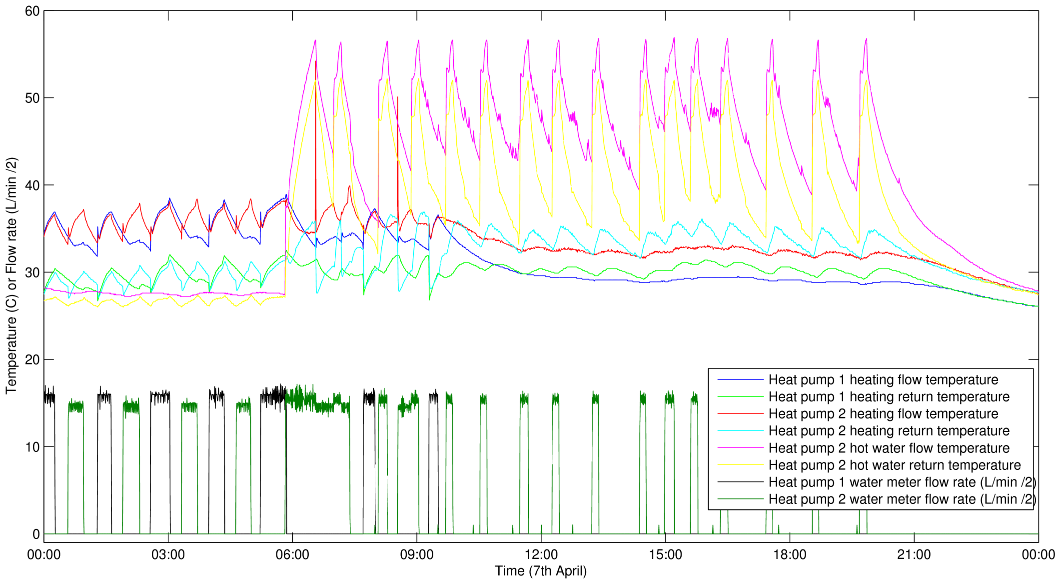


Figure 16: Graph of pipe temperatures and water flow rates through the two ground source heat pumps providing heat to the first long-term monitoring house. Hot water is only provided by heat pump 2. Note that pipe sensors can show sympathetic rises even when there is no flow due to thermal conduction through the copper, and the arrangement of sensors along the pipes.

The second house is heated by an air-source heat pump, and full Passiv monitoring has been installed since the end of April 2011. During this time a volume of more than 10^6 litres was measured by the water meter. The table below shows COP calculations for some example days; COP is separated into values for heating and hot water, and also a value that includes the electrical consumption of the heat pump controls, pumps, and valve. In addition, figures for the average input power (i.e. electric supply) and output power (i.e. calculated heat) are shown. Figure 17 shows a recent day's data.

Air-source heat pump **Day** (00:00 to 23:59)	**COP (overall)**	**COP (heating)**	**COP (HW)**	**COP (inc. electrics)**	**Average input electrical power (kW)**	**Average output thermal power (kW)**
28th April	2.49	2.54	1.85	2.22	0.82	2.04
9th May	2.76	2.90	1.59	2.33	0.48	1.33
21st July	2.46	2.58	1.98	1.85	0.24	0.58

One might expect the COP to be significantly higher in the summertime, but in fact the heating on the 21st July was done overnight when the external temperature was actually quite similar to the earlier dates.

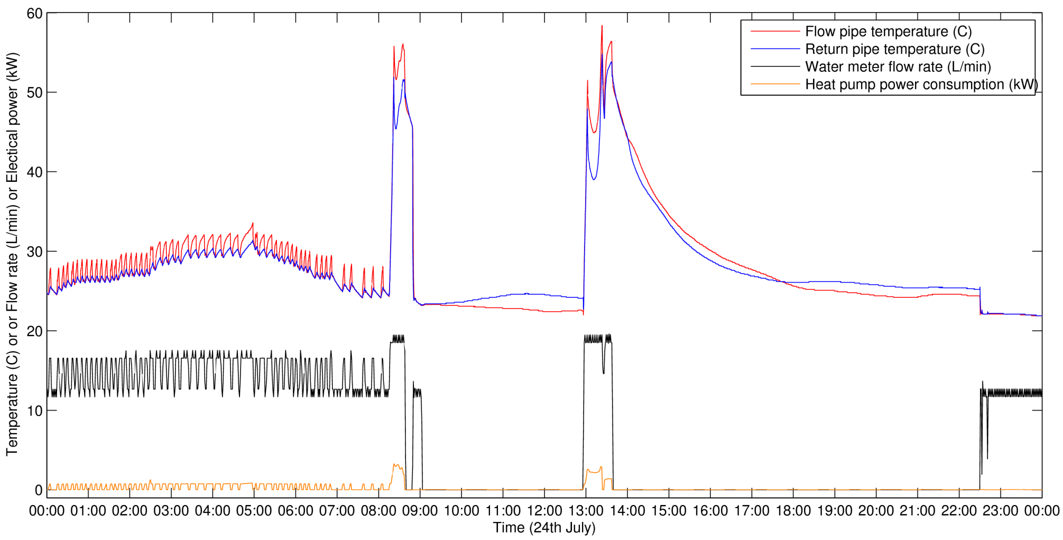


Figure 17: Graph of pipe temperatures, water flow rates, and electrical power consumption for the air-source heat pump in the second long-term monitoring house.

3.7 Solar thermal

A home was identified that has a solar thermal system providing a supply of hot water (in addition to a biomass boiler, but this was not included in this investigation). In this section we describe the use of this location to test a Grundfos heat meter against a Syxthsense WZCD heat meter, but the property was also used to test the Passiv pipe temperature sensors (Section 3.1) and the non-invasive flow meters (see Section 3.8 below).

A Grundfos VFS flow meter was installed on the return from the solar thermal tubes, and together with a PT100 temperature sensor on the solar collector this comprises a heat meter (with the assumption that the temperature at the collector is the same as the flow pipe). The heat calculation is done by a Steca TR0603mc controller, which is very similar to the HMDII used above, but it is capable of logging temperatures and flow rates in addition to heat. For comparison, an Syxthsense WZCD compact heat meter is installed in series with the Grundfos VFS. Its flow temperature PT500 sensor is attached to the pipe from the solar tubes (and insulated). The Grundfos might be expected to overestimate heat as there may be losses between its sensor at the collector and the Syxthsense sensor at the meters.

Results. Four months' data are available; a graph of a typical day is shown in Figure 18 below. The total volume and heat figures for two periods is shown in the table below.

For the initial monitoring period, the Steca controller was expecting signals from a different model of Grundfos VFS sensor which meant that flow rates were misinterpreted. We have been able to correct for this, and the figures in the table include this correction; however it is not possible to correct the heat figures as easily since they depend on the temperatures as well. During the second monitoring period, the Steca was configured correctly.

Test	Volume/L (Syxthsense)	Volume/L (Grundfos)	Heat/kWh (Syxthsense)	Heat/kWh (Grundfos)
Solar thermal (3rd to 26th July) *(Percentage difference)*	68886	65749 *(-4.6%)*		
Solar thermal (11th August - 5th October) *(Percentage difference)*	130890	96720 (-26%)	1161.6	1123.2 *(-3.3%)*

Discussion. The metered volumes agree well for the first period, but there is a significant discrepancy for the second period. We believe this is because the Steca controller logs flow rates to the nearest litre per minute, and at the usual flow rate of ~4.5L/min it reports 4L/min and thus underestimates flow. For the mis-configured Grundfos in the first period however, much higher integers are reported, reducing this discretization error.

The total metered heat energy figures agree very well (confirming perhaps that the volume discrepancy is a logging problem).

In summary, the Grundfos heat meter produces matching energies to the standards-approved heat meter; the volume discrepancies are just a logging anomaly.

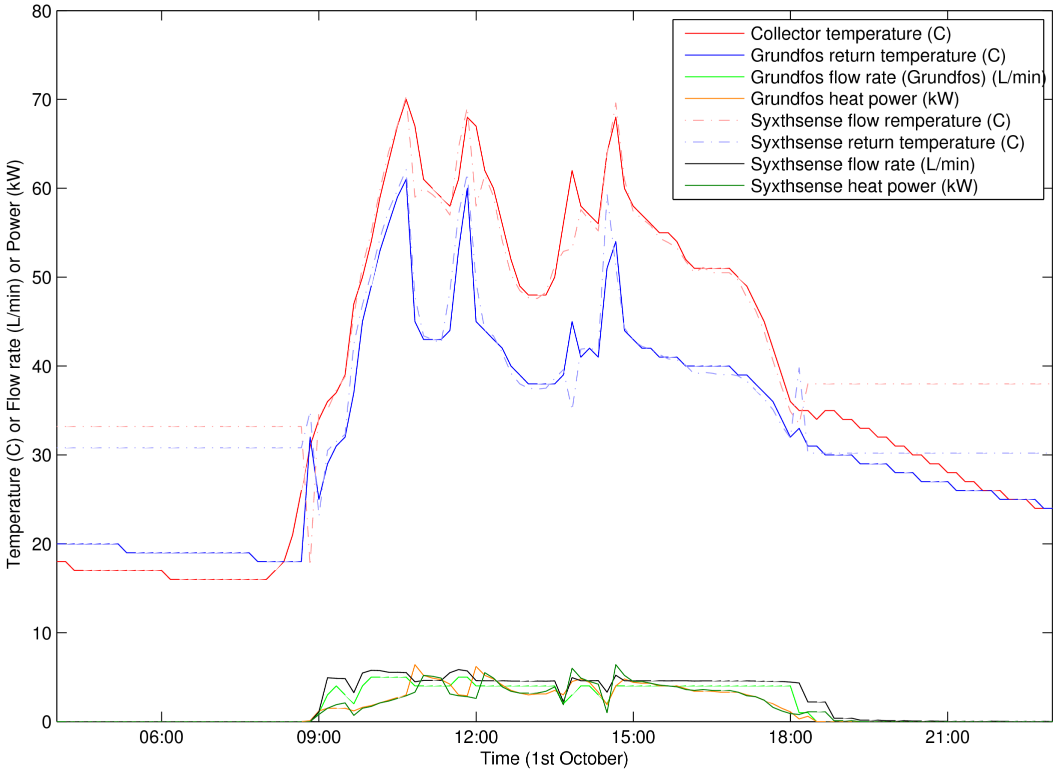


Figure 18: Graph of temperature, volume flow rates and heat powers produced by a solar thermal collector, as measured by a Syxthsense heat meter and the Grundfos heat meter.

3.8 Non-invasive flow meters

Two different non-invasive flow meters were trialled within this investigation. A Solenvis SL2 meter was compared against a water meter measuring consumption for the whole of a house (another Syxthsense-supplied device, providing measurements in litres), and also as a heat meter on the solar thermal system of the previous section (compared against a Syxthsense WZCD heat meter).

A Micronics Portaflow 330 meter was compared against the same whole-house water consumption meter, and also trialled in the Newbury Test Rig against the Syxthsense water meter. It was also tested on a conventional gas boiler system as an example heat metering application (in conjunction with Passiv temperature sensors), aimed at providing boiler efficiency measurements. There was no conventional flow meter available for comparison at this site.

Results (Solvenis). The table below shows the results of comparing the Solenvis non-invasive meter with the Syxthsense flow and heat meters. A photograph of a Solenvis measurement is shown in Figure 19.

In each case the Solenvis was set up carefully according to the supplier's instructions, and in fact a Solenvis representative was present for some of the tests. The W configuration of the sound wave was chosen so that a reasonable separation between the transducers could be used. The meter was about 1.5m from the nearest bend in the pipe, and the Solenvis display indicated good signal quality. A vertical section of return pipe was chosen so there were no air bubbles, and the fluid in the system was clean and clear.

Test	Volume/L (Syxthsense)	Volume/L (Solenvis)	Heat/kWh (Syxthsense)	Heat/kWh (Solenvis)
Manually drawn 100L (15mm pipe; flow rate ~720L/h; 20 tubs of 5L filled) *(Percentage difference)*	103 (whole-house consumption meter)	39 *(-62%)*		
Larger volume measurement (15mm pipe; flow rate ~720L/h; velocity 0.6m/s, which is above acceptable minimum for SL2) *(Percentage difference)*	1001 (whole-house consumption meter)	426 *(-57%)*		
Solar thermal (13th - 14th June) (22mm pipe; 30%/70% glycol/water, speed of sound assumed 1546m/s) *(Percentage difference)*	3000 (nearest 1000)	1620 *(-20% to -40%)*	45	19.5 *(-57%)*

Discussion (Solenvis). These results show that the Solenvis SL2 consistently reports flow (and therefore heat) almost a factor of two smaller than the other meters. Other shorter tests were carried out as well, and similarly found inconsistent and significantly lower flow measurements. Temperature reports from the two heat meters are consistent to about 1°C, but this is not surprising as both use standard PT100 temperature sensors.

Figure 19: Photograph of the Solenvis SL2 in operation, with the transducers in the background.

Results (Micronics). The table below shows the results of five tests comparing the Micronics non-invasive flow meter against the whole-house consumption water meter. The water temperature was measured to be 17°C before the first test and 13.5°C after the second test, and the Micronics configured accordingly.

Test (all 15mm vertical copper pipe, 0.8mm thickness)	**Volume/L** **(Syxthsense whole-house)**	**Volume/L** **(Micronics)**
Flow test, with Micronics set to 17°C *(Percentage difference)*	99	102.86 *(+3.8%)*
Flow test, with Micronics set to 17°C *(Percentage difference)*	88	105.91 *(+20.3%)*
Flow test, with Micronics set to 13.5°C *(Percentage difference)*	103	104.60 *(+1.5%)*
Flow test, with Micronics set to 13.5°C *(Percentage difference)*	101	102.88 *(+1.8%)*
Flow test, with Micronics set to 13.5°C *(Percentage difference)*	1028	1005.6 *(+2.2%)*

The Micronics was also installed for one morning at the Newbury Test Rig. The results of this test in comparison with the Syxthsense water meter are shown in the table below.

Test (15mm vertical copper pipe, 0.8mm thickness, 40°C)	**Volume/L** **(Syxthsense water meter)**	**Volume/L** **(Micronics)**
Flow test *(Percentage difference)*	23	19.35 *(-14-18%)*

Finally, the Micronics Portaflow 330 was installed for two days on the flow pipe from a conventional gas boiler (in a further property, not previously used in this study). The device's impulse output (one pulse per litre) was connected to a Passiv WSC to enable remote logging of flow. Passiv pipe temperature sensors were available on the flow and return pipes. This arrangement comprises a complete non-invasive heat meter. Gas meter readings were also taken during the test, meaning that the efficiency of the boiler could be calculated. We have assumed a calorific value of 39.1 MJ/m^3 [18] and the standard volume correction factor of 1.022640.

Test (all 22mm vertical copper pipe, 0.9mm thickness, 40°C)	**Volume/L (Micronics)**	**Heat /kWh (Micronics +Passiv)**	**Gas consumption (m^3)**	**Boiler efficiency**
Hot water cycle (28th Sept, am)	314	2.51	0.3148	71.8%
Space heating (28th Sept, pm)	89	1.14	0.1784	57.5%
Hot water cycle (29th Sept, am)	390	2.96	0.3547	75.1%
Space heating (29th Sept, pm)	346	3.76	0.476	71.1%
Hot water cycle (30th Sept, am)	236	3.00	0.3822	70.7%
Overall	1375	13.37	1.7061	70.6%

Discussion (Micronics). The Micronics Portaflow 330 performs very well, and usually meters volume to within a few percent of a conventional water meter. In two cases it was out by up to 20%. The outlier in the first set of tests is not explained by the changing temperature of the incoming fluid.[6] The discrepancy at the Newbury Test Rig is not explained by temperature changes either; the inaccuracy here is likely to be due to the extremely variable flow rate (and non-smooth flow) of hot water consumption at a tap.

The boiler efficiencies calculated with the Micronics meter are very plausible. The boiler (an Ideal Classic FF260) has a SEDBUK seasonal efficiency figure of 76.7%, so actual efficiencies slightly lower than this would be expected, especially given that the temperature sensors were installed some way from the boiler and thus there will be some pipe work losses included. The low efficiency figure for the space heating on 28th September is due to the shortness of the heating period: a disproportionate amount of energy goes to fixed losses such as heating up pipework.

In summary, the Micronics non-invasive flow meter performed well enough to be a valuable temporary device for measuring efficiency or coefficient of performance with no plumbing required, although it is susceptible to occasional errors of 20%.

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6 A change in temperature of a few degrees will change the speed of sound, and thus the metered volume estimated by the Micronics ultrasonic meter, by 1-2% at most. There is a 5% change in the speed of sound between water at 20°C and 70°C.

4. Conclusions

This project has provided a wide-ranging investigation into heat metering, covering a variety of heat meters applied to several completely different heating systems. Our conclusions are as follows:

- On suitable installs, the **Passiv heat meter** can give long-term accuracy better than ±4% compared to standards-approved compact heat meters. Its ability to continuously monitor temperature and flow separately provides a valuable diagnostic tool; and the same temperature measurements can be used for other purposes such as consumption analysis and control.
- The **Grundfos heat meter** can also give long-term accuracy better than ±4% compared to standards-approved compact heat meters. With a comprehensive interface, Passiv-linked Grundfos sensors would comprise an excellent remote heat metering solution. Our only concerns are the low nominal accuracy of the Grundfos temperature sensors, and the slightly awkward grounding and calibration requirements of the Grundfos sensors.
- The **Solenvis non-invasive ultrasonic flow meter** is not suitable for domestic flow and heat metering, as it usually underestimated flow by a factor of two. However, the **Micronics** non-invasive flow meter performed well; together with Passiv components it provides a valuable, remotely-monitored heat meter with no plumbing required.
- Proper physical installation of a heat meter is very important, particularly for the temperature probes, as heat metering is very sensitive to the quality of these measurements (especially when the flow-return temperature difference is low, such as for a heat pump at low power). If non-invasive temperature probes are used, it is important to have good thermal contact with the pipework and lagging around the outside of the probes, otherwise heat can be significantly underestimated. A disadvantage of using pulse output heat meters is that individual temperatures are unavailable for analysis (such as into the cause of discrepancies).
- Heat metering of **domestic hot water consumption** is potentially difficult due to short bursts of water usage and rapid changes of pipe temperature. The Passiv and Grundfos heat meters gave readings 15-20% higher than the Integral-V compact heat meter in our test rig.
- Measuring volume flow for a **gravity-fed system** is likely to be very inaccurate due to long periods of slow convective flow. Nevertheless, the vast majority of *heat* is transferred during other periods and can be more accurately measured.
- The successful remote monitoring of the sites (and back-end processing) by PassivSystems demonstrates that manual meter reads are not required for heat metering, removing one potential barrier to widespread heat metering for heat incentive schemes or community heating projects.

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