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Production efficiency of hot water for domestic use

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ABSTRACT

This paper examines the efficiency (in terms of energy use and carbon emissions) with which 5 different types of domestic water heating systems employed in the UK are able to produce hot water for sanitary use. A method of normalisation is employed allowing results from case studies with different systems and usage levels to be compared. Water heating appliances studied include gas boilers, a micro CHP, heat pumps, an immersion heater, and a solar thermal system. It is found that instantaneous production of hot water is much more efficient than delivery via tank storage for gas-fuelled systems. For electrical systems, an immersion heater is found to perform better in some circumstances than heat pumps and also has advantages when combined with a solar thermal system leading to the proposal that this combination offers the most potential as a low carbon method for domestic hot water provision in the long term. Opportunities are identified to improve the performance of all systems with storage through better control of heat inputs. Inconsistencies in, and problems of compliance with, established standards for mitigation of *Legionella* in hot water systems are also identified.

1. Introduction

Regulatory measures aimed at mitigating climate change and economic pressures from rising fuel costs are motivating increased energy efficiency within the UK residential sector, which accounts for 32% of UK final energy consumption [1] and a similar proportion of CO_2 emissions. Historically space heating has been the major use of energy in UK homes amounting to 61% of the total in 2009 (Fig. 1), while water heating, appliances, lighting and cooking comprise the balance. However, as standards of insulation improve with retrofit programmes initiated under the UK Low Carbon Transition Plan [2] this element can be expected to fall. Realisation of the policy goals in this plan such as 80% reduction in UK CO_2 emissions by 2050, with no emissions at all from the domestic sector, is therefore likely to require attention to these secondary energy uses. As the third largest element water heating is clearly worthy of detailed examination.

This paper focuses on the energy consumption involved in the production and use of domestic hot water for washing and other sanitary purposes, with the aim of comparing efficiency and carbon intensity across the range of water heating systems commonly installed and identifying opportunities for improvement and implications for policy. Table 1 provides a demographic summary of current fuel and system types derived from the 2009 English Housing Survey (Department of Communities and Local Government (DCLG) [3]. A critical distinction made in Table 1 is between those systems which include a tank for storage of hot water (55% of the total), and those where hot water is produced on-demand (45%). The existence of a tank provides opportunities for fuel diversity and optimisation of efficiency which are discussed later, but results in some level of unavoidable losses arising from a standing volume of hot water. Some other points of clarification to aid interpretation of the table are:

- "Economy 7" refers to a electricity tariff option available in the UK under which electricity is supplied within a 7 h overnight time window at a lower cost and also lower carbon intensity.
- "Combi" refers to a type of gas boiler which provides space heating by circulating hot water through a radiator network and heats water directly from the mains supply to deliver domestic hot water on demand.
- "Other fuels" comprise oil and solid fuels such as coal or biomass.

Because of the complexity of instrumentation and analysis required to quantify the amount of hot water used in a household and the energy consumed to provide it the approach adopted for the present work comprises a set of 7 case studies. Each case is a single household and water heating system for which hot water use and energy inputs have been analysed in detail for a sufficient

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Table 1
Populations of different water heating methods in England [3].

System type	Storage (S) or instantaneous (I)	Number of dwellings (000s)	Proportion of total (%)
Electrically heated, on-demand	I	340	1.5
Electric immersion heater, normal tariff	S	612	2.7
Electric immersion heater, Economy 7	S	1673	7.5
Gas fired non condensing "combi" or water heater	I	5498	24.8
Gas fired condensing "combi"	I	4061	18.2
Gas fired non condensing with tank	S	7653	34.3
Gas fired condensing with tank	S	1331	6.0
Other fuels with tank	S	1122	5.0

number of days to estimate the performance of the system used. By performing this analysis across a range of system types it has been possible to draw some more general conclusions based on the inherent physics of the system engineering and results from other studies that have investigated patterns of hot water use. Some of the case studies include system types (micro CHP and heat pumps) which are relatively novel in the UK and for which comparative data on hot water production efficiency is useful to assess their potential benefits in larger scale use. All of the systems studied had been installed on a retrofit basis and had been in operation for at least two years so they exemplify performance currently achieved in practice rather than optimum performance for each system type.

The rest of the paper is organised as follows. Section 2 summarises the user demand patterns and regulatory requirements applicable to hot water systems in the UK, drawing out a particular issue concerning protection against *Legionella* risks. Section 3 describes the systems studied and the methodology for normalisation of results. Section 4 presents results in terms of energy efficiency and carbon dioxide emissions for the fuel-using systems when operated on their own and in combination with solar hot water heating. Sections 5 and 6 discuss the implications of these results and the conclusions for policy and installation practice.

2. Background

2.1. Hot water use

A detailed investigation of current patterns of domestic hot water use in the UK was performed by the Energy Saving Trust (EST) who monitored 120 dwellings in 2008 [4]. They found average hot water consumption per household varying from less than 25 L/day to over 300. They were able to derive a model relating daily volume used in litres V to the number of occupants N:

$$V = 46 + 26N \quad (1)$$

with standard errors of ±22 on the intercept and ±7 on the slope. This model is used later to assess the suitability of each system type for different household sizes. It is reasonably consistent with an alternative simple model of 53 L per occupant per day proposed by Yao and Steemers [5] but seems more plausible since there will tend to be some economy of scale for larger households.

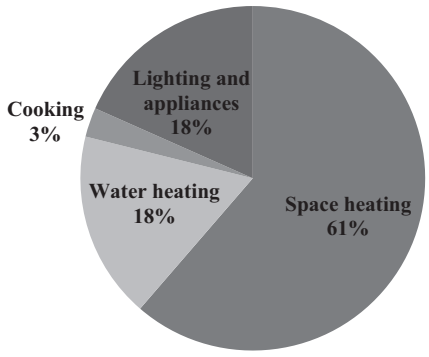

Fig. 1. UK domestic energy consumption by end use in 2009 [1].

The UK's strategy for water provision "Future Water" (Department for Environment, Food and Rural Affairs, DEFRA) [6] seeks to drive down overall domestic water consumption from 150 L per person per day to 130 L by 2030. Measures include the Code for Sustainable Homes [7] which specifies hot water saving features such as aerating showers and taps for new buildings. However Critchley and Phipps [8] identify trends for increased hot water use in existing homes through more frequent showering and installation of shower pumps. The introduction of universal metering by 2030 envisaged by DEFRA [6] and the development of standards for water consuming products under the Market Transformation Programme [9] are aimed at mitigating these trends.

2.2. Safety requirements

The critical mandatory safety requirements for provision of domestic hot water in the UK are specified in Building Regulations Part G [10]. These focus on preventing water boiling anywhere in the system through safety cut-out mechanisms controlling all heat sources that operate independently of thermostatic control. They also seek to prevent scalding from delivery of water at too high a temperature at the tap by requiring mixer valves to be employed such that the distribution temperature is limited to 60 °C and the water emerging from a bath tap does not exceed 48 °C. More detailed interpretations of the law and implementation recommendations are given in British Standard 6700 [11] invoked by [10] which also introduces the need for hot water systems to include measures to reduce risks from bacteria particularly *Legionella*. Paragraph 5.6.3 includes the commentary "In order to reduce the risk of colonisation ... hot water should be stored and distributed at a temperature of not less than 60 °C". Clearly a practical system with temperature tolerances on mixing valves and thermostats would be unable to satisfy both this requirement and Part G. Since the commentary is taken from a Health and Safety Executive Code of Practice [12] for controlling *Legionella* in workplaces and public buildings it is perhaps not surprising that it is not easily applied to the domestic environment.

None of the systems monitored for this study maintained hot water continuously at 60 °C and for systems with storage, draw-off volumes per day were often greater than the volume of the tank. Since no part of the storage volume was maintained permanently at 60 °C, none of the systems could assure that all water delivered had at some time been raised to 60 °C. System hot water delivery temperatures (i.e. prior to any mixing for avoidance of scalding) ranged from 40 °C to 68 °C. The EST study [4] also found that delivered hot water temperatures ranged from below 42 to above 62 with a mean of 52 °C, with "combi" systems having a lower average temperature (49 °C) than systems with tank storage (53 °C). These temperatures cover both the range at which references such as [12] advise *Legionella* flourish (35–45 °C) and that where they are killed

Table 2
Case study systems.

Fuel	Technology and (system diagram)	Storage (S) or instantaneous (I)	Number of systems evaluated
Gas	Non condensing "combi" boiler (Fig. 2)	I	2
Gas	Non condensing conventional boiler with simple water temperature control (Fig. 3)	S	1
Gas	Non condensing conventional boiler with improved water temperature control (Fig. 3)	S	1
Gas	Micro CHP with simple water temperature control (Fig. 3)	S	1
Gas	Micro CHP with improved water temperature control (Fig. 3)	S	1
Electricity	Immersion heater (Fig. 4)	S	1
Electricity	Heat pump (Fig. 5)	S	2
Solar	Flat plate panel with direct circulation (Fig. 4)	S	1

(above 55 °C). It seems that the main mitigation measure in practice is avoidance of stagnation.

The literature concerning the observed incidence of *Legionella* in domestic plumbing is limited but a study of 452 hot water systems in Germany by Mathys et al. [13] provides useful evidence. The instantaneous water heating systems they analysed (52 out of the 452) were free from *Legionella*, but a prevalence of 5.5% was found in the 343 systems with storage tanks that did not use district heating and hence were comparable to the present study. The temperature of the delivered hot water at the tap was found to be the most important determinant of *Legionella* concentration. Given the difficult trade-off between reduced energy efficiency and scalding risks at higher temperatures, and *Legionella* at lower temperatures, there is a need for further research to identify the actual risks presented by *Legionella* in domestic hot water systems, particularly given the increasing use of showers noted by Critchley and Phipps [8] which are a known source of *Legionella* exposure [14], so that effective and unambiguous guidance can be given to system designers, installers and consumers.

3. Hot water systems compared

3.1. System types studied

The system types covered in the case studies are summarised in Table 2 and illustrated by outline system diagrams in Figs. 2–5. The instantaneous gas systems (known as "combi" systems – Fig. 2) simply consist of a heat exchanger which transfers combustion heat to water at mains supply pressure which is then fed to taps and showers. Combustion is initiated by the flow of water that occurs when a tap is opened by the user, so there tends to be a delay in the arrival of usable hot water at the point of use while the heat transfer builds up. When the user closes a tap, combustion ceases, but there is a volume of hot water in the heat exchanger and pipes which then cools down. These losses at the start and finish of each draw-off are the main source of inefficiency in the system.

The conventional gas system and the micro CHP both employ a configuration shown in Fig. 3 which is typical of UK systems with storage. It comprises a boiler unit and a separate insulated tank usually between 100 and 200 L capacity which is fed from a header tank installed in the loft space of the house. This decouples the hot water distribution from the mains supply so that by default it operates with the pressure provided by the header tank. This is not always adequate for showering so in the case of the conventional gas system studied a pump was fitted to the feed to the shower. The only difference to water heating arising from the electricity generator fitted to the micro CHP is that the higher thermal inertia in the CHP unit and the complexity of the shut down process means that heat continues to be delivered to the storage tank for some time after a request for water heating is dropped. This leads to a benefit from thermostatic regulation that takes this effect into account.

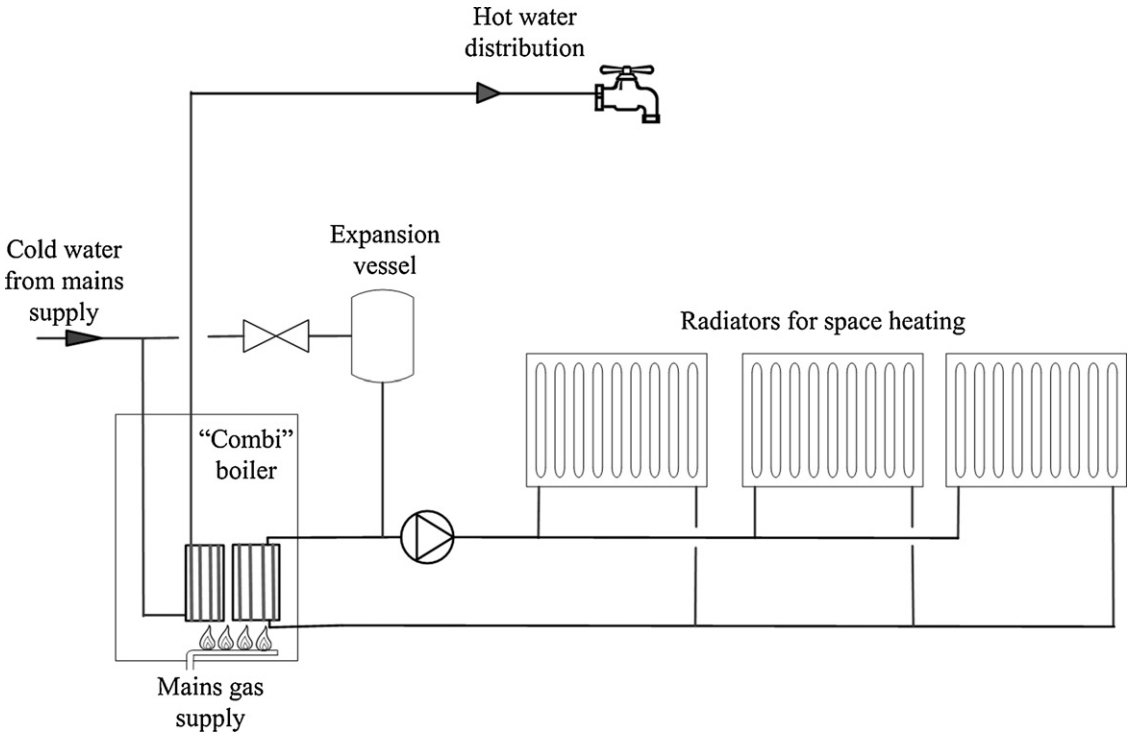

Fig. 2. "Combi" gas boiler system.

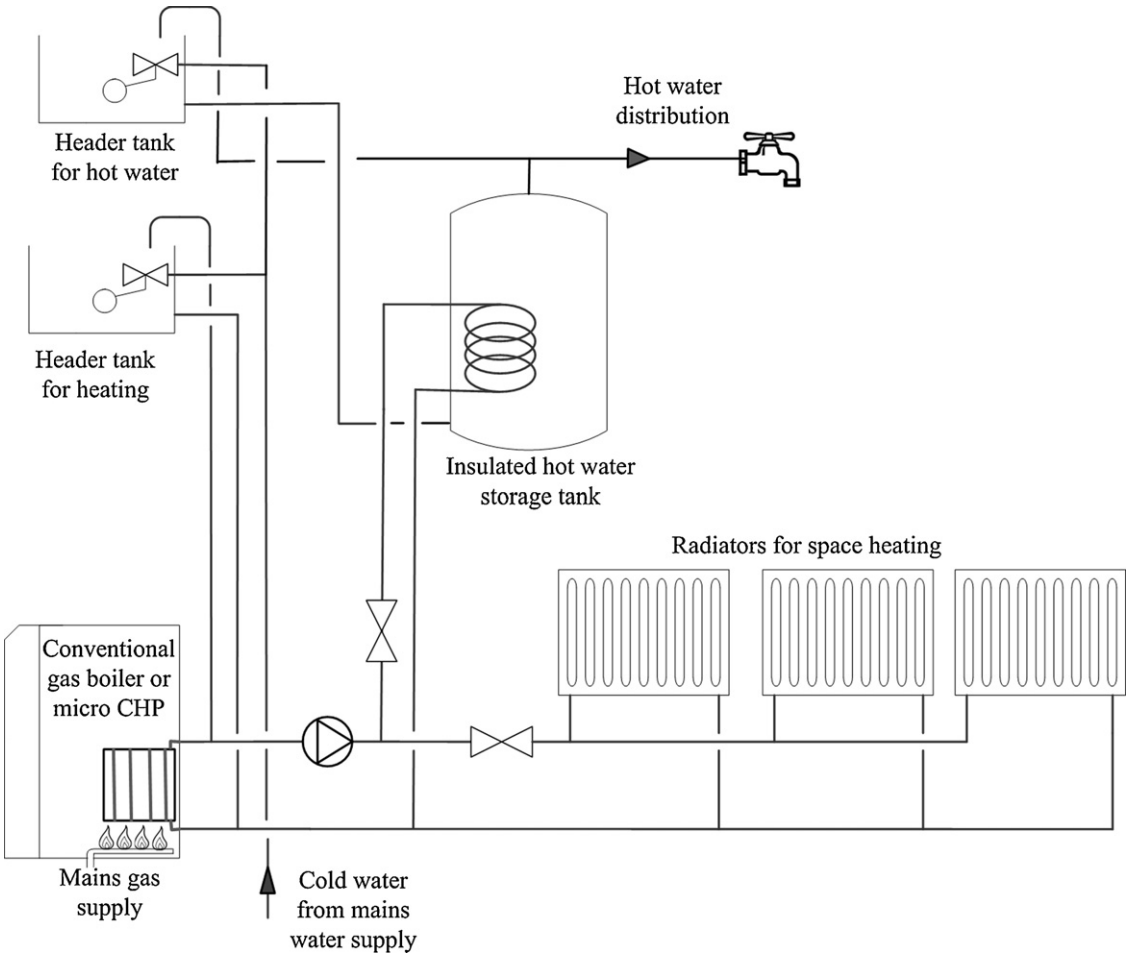

Fig. 3. Conventional gas boiler system with hot water storage.

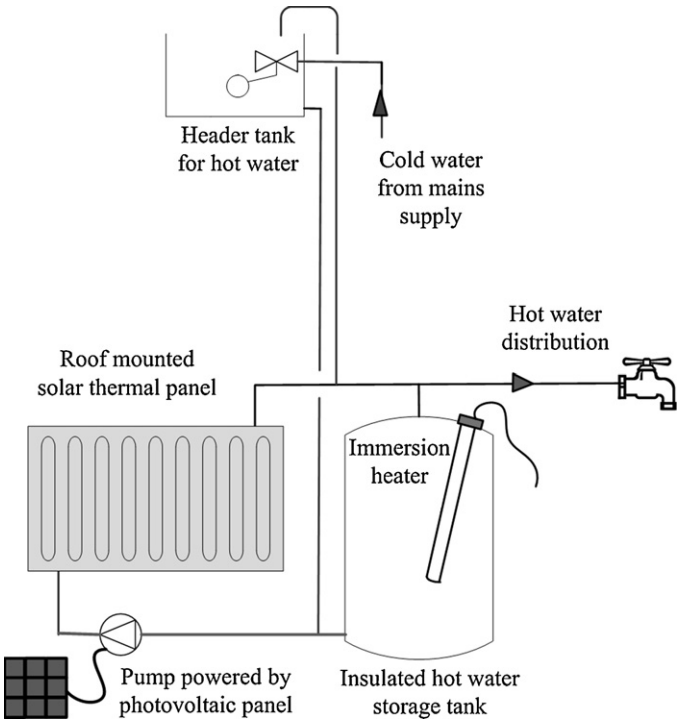

Fig. 4. Solar thermal system with immersion heater.

Both these systems were evaluated initially as originally installed with temperature control of the stored water by a simple bimetallic strip thermostat with a hysteresis of about 10 °C as fitted to many UK systems of this type. This was then replaced with an electronic sensor and control device aimed at improving efficiency that ensured heating to a temperature of about 60 °C took place only once per day to mitigate the *Legionella* risk and at other times a lower temperature threshold of about 45 °C was maintained. This pattern of control provided by this device can be seen in Fig. 6. The evaluation was then repeated to determine the benefit.

The electric immersion heater was also fitted to an insulated tank with a header tank as shown in Fig. 4. This arrangement is often found in conventional gas systems where the immersion heater is installed as a backup for use when the boiler fails or is being maintained. This system included solar water heating by a 2 m^2 flat plate panel which circulated water directly to and from the tank (i.e. without a separate heat exchanger) driven by a small pump which being powered by a photovoltaic panel only circulated the water when useful solar energy was available. The energy captured by the solar thermal panel was measured using a flow meter and temperature sensors on the flow and return connections to the tank. To characterise the immersion heater operating on its own the solar thermal input was cut off while its performance assessment took place.

The ground source heat pump systems studied (Fig. 5) have a 165 L insulated tank fed directly from the cold water mains supply. This is heated by a primary pumped water circuit with two heat exchangers, one taking heat from the condenser and the other conveying heat to the tank. To simplify installation all the system

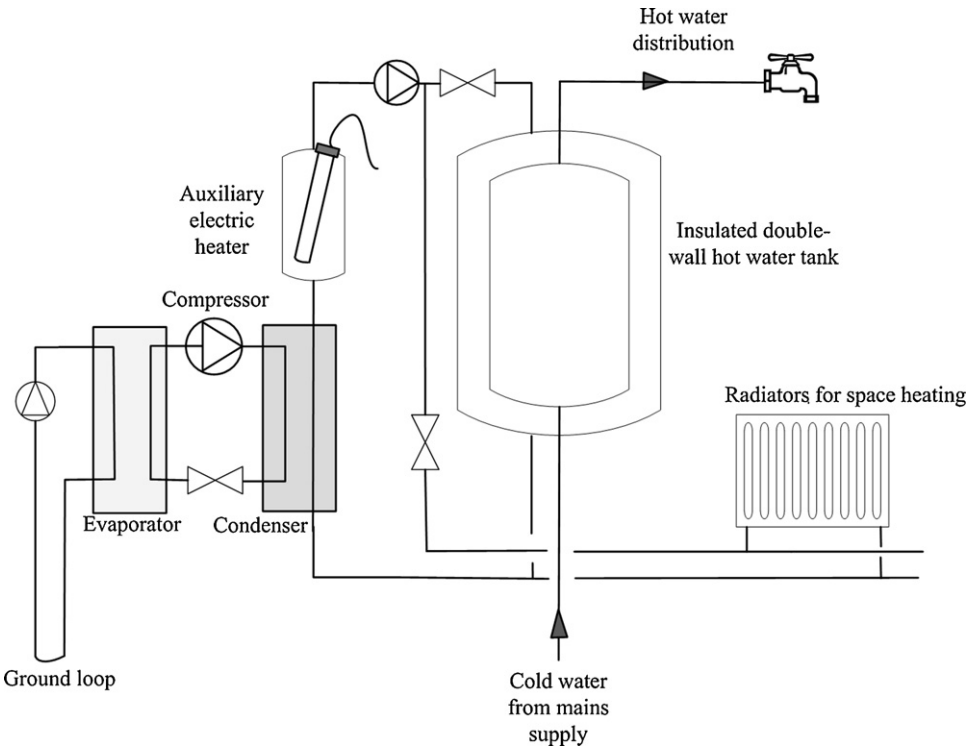

Fig. 5. Ground source heat pump.

components including the tank are packaged by the original equipment manufacturer in a single enclosure which because it is quite bulky has been installed outside the insulated fabric of the building in the case of the systems studied (although protected from frost). Instrumentation and measurement methods were as described by Stafford [15] where the total heat output of the heat pump and the heat supplied to space heating are measured giving the heat supplied to hot water by subtraction. The allocation of electricity inputs to the compressor between space heating and water heating was performed using the ratio of the heat output supplied for each purpose. To minimise the error arising from the use of this ratio, due to differences in the coefficient of performance (COP) between space and water heating, measurements from the summer were employed for the main performance assessment in this study when at least 75% of the heat output was employed for water heating.

3.2. Methodology

For each system studied, the volume of hot water drawn off over a 24-h period (V_m) has in most cases been measured directly or via the cold water feed using a flow meter. Where this was not available but detailed tank temperature measurements had been taken, an approximate estimate of the draw-off volume was deduced from the energy balance. This calculation used the overnight cooling curve (from 00:00 to 05:30 in Fig. 6) to estimate heat losses from the tank and the transitions in temperature (such as those at 13:45 and 20:10) were combined with the total volume of the tank to estimate the volume and temperature of draw-offs. The energy input Q_i to the system was measured using heat meters and gas and electricity metering as appropriate.

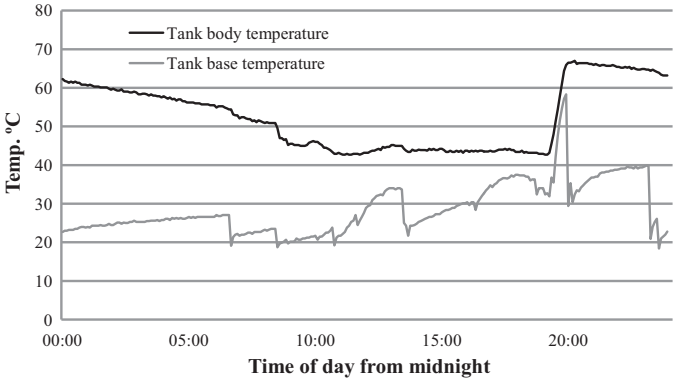

Fig. 6. Example of storage tank temperature daily profile.

In order to compare the performance of different hot water production systems which are subject to a wide variety of usage patterns and operating temperatures it is essential to find some method of normalisation. The approach adopted is to take the maximum supply temperature of 48 °C prescribed by Building Regulations Part G [10] as the benchmark temperature for delivery of hot water to the user. Where the measured temperature T_h of hot water from the system is higher than this (as is usually the case) a volume V_n is calculated of cold water from the mains supply at a temperature T_c (as measured for the system under analysis) that would have been required to dilute the hot water to 48 °C and added to the measured volume V_m delivered to give a normalised volume. This corresponds exactly to the expectation in Part G that a mixing valve will be fitted on the system output. The required additional volume V_n is given by:

$$V_n = \frac{V_m(T_h - 48)}{48 - T_c} \tag{2}$$

Where the measured temperature is lower than 48 °C the volume is left constant and the measured energy input Q_i adjusted in proportion to the temperature deficiency. The normalised energy input Q_n is given by:

$$Q_n = \frac{Q_i(48 - T_c)}{T_h - T_c} \tag{3}$$

The efficiency of the production process can then be defined with a local system boundary as the energy added between mains

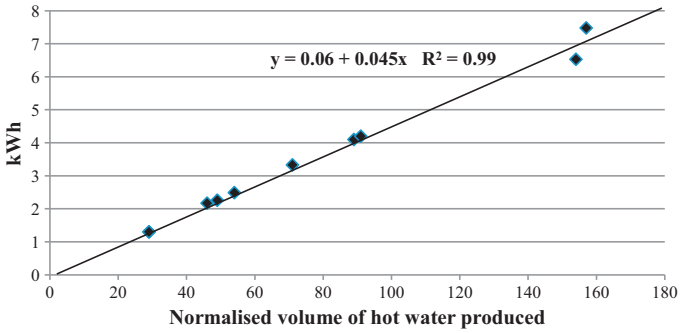

Fig. 7. Efficiency of instantaneous production of hot water by a "combi" gas boiler.

feed and tap to the volume delivered divided by the energy input from gas or electricity mains supplies, the volumes and energy used either actual or normalised as appropriate. However this comparison of systems must also respond to the European Union policy requirement expressed in standard EN 15603 [16] that the energy performance of buildings be evaluated in terms of primary energy use and carbon dioxide emissions. Primary energy use for fuel sources is calculated by multiplying the local energy input to the system under consideration by a primary energy factor which reflects all the losses in the national supply chain. For this study UK primary energy factors (1.112 for gas, 2.580 for grid electricity) are taken from [17] and carbon emission intensities (0.184 kg CO_2/kWh for mains gas, 0.485 kg CO_2/kWh for electricity) from [18].

4. Results

For each of the monitored systems, the energy input and normalised hot water volume output were determined for a sufficient number of days to allow a relationship of the form $y = a + bx$ to be obtained by regression. Two examples are shown in Figs. 7 and 8. The first shows results from one of the gas combi boilers where the dependence of losses on the number of draw off events ensures that these losses are reflected in the regression slope and the y axis intercept is near zero. The second from one of the heat pump cases is typical of storage systems in that the fixed minimum losses from the tank and primary circuit are indicated by the y axis intercept while the slope gives the marginal cost of heating the water.

The linear models of the performance of each system obtained in this way are summarised in Table 3 accompanied by an efficiency figure determined from the models for delivery of 100 L at 48 °C with an assumed cold feed temperature of 18 °C which is an average figure for July as found by EST [4]. All the models in the table are derived from measurements in the summer months. The figure of 100 L is chosen as a benchmark because it is close to the expected

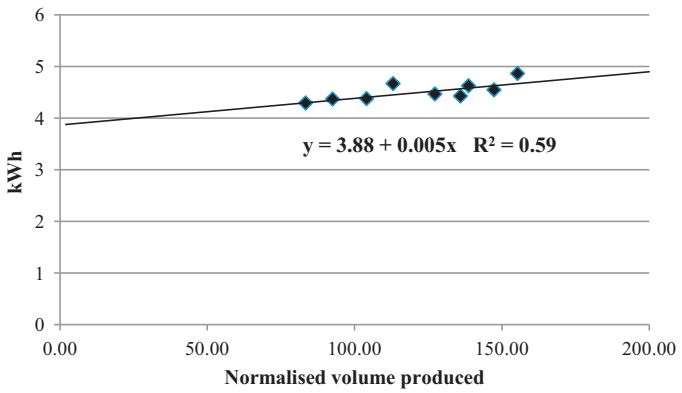

Fig. 8. Efficiency of production of hot water by ground source heat pump (2).

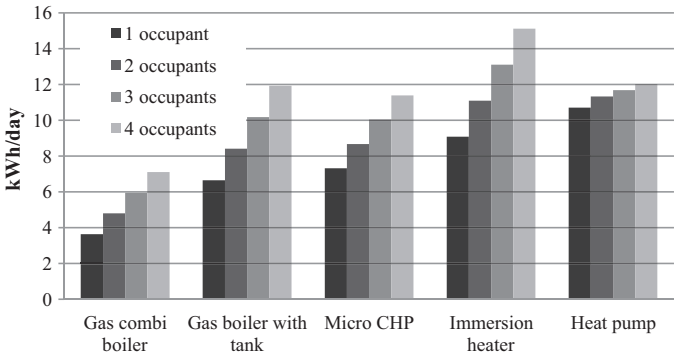

Fig. 9. Primary energy requirement of systems by occupancy.

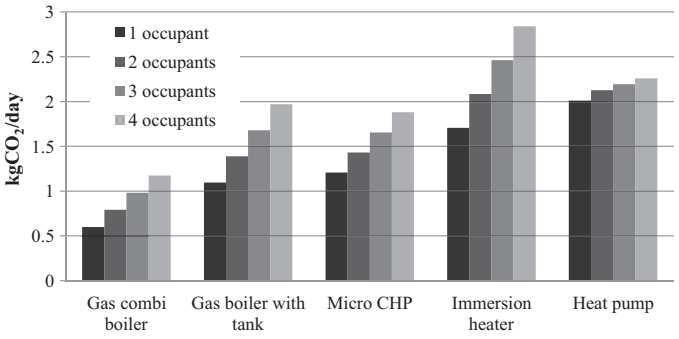

Fig. 10. CO_2 emissions of systems by occupancy.

consumption for a household of 2 persons using both the models from Refs. [4,5]. The average household size in England was 2.3 in 2006 and is expected to fall to 2.2 by 2016 [19]. The performance models in Table 3 can be combined with the model given by Eq. (1) relating hot water demand to occupancy to compare the primary energy consumption and carbon emissions of each system for different household sizes. Fig. 9 compares the primary energy consumed while Fig. 10 compares carbon emissions.

To allow comparison of the solar hot water subsystem with these models based on fuel use a histogram of the daily energy output over a year is shown in Fig. 11. The total for the year (2009) was 575 kWh. This is on the low side compared with other studies of solar hot water performance in the UK such as EST [20] which obtained a median output of 1140 kWh from a sample of 88 installations. However, this was a 2 person household with lower than average usage which reduces solar output. Using the data collected from this solar hot water system and the models in Table 3 it is possible to assess how each of the heating systems would have

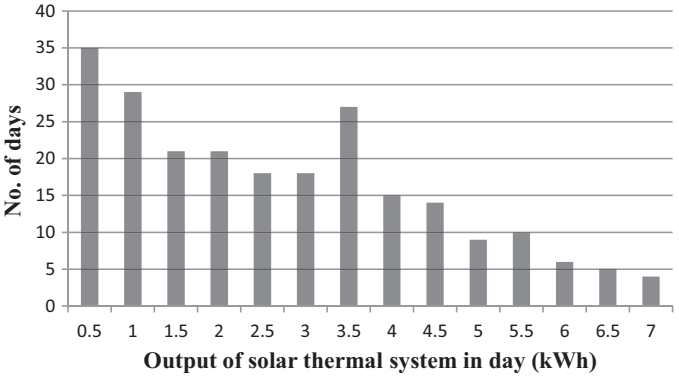

Fig. 11. Histogram of solar thermal output over a year.

Table 3
Performance models derived from experimental measurement.

System evaluated	Fixed losses (kWh/day)	Marginal cost (kWh/L)	R^2	No. of observations	Efficiency at 100 L/day
Gas "combi" boiler (1)	0.06	0.045	0.99	10	76%
Gas "combi" boiler (2)	0.39	0.040	0.94	11	79%
Gas conventional, simple control	2.53	0.061	0.81	7	40%
Gas conventional, improved control	1.58	0.061	0.93	13	45%
Micro CHP with simple control	5.26	0.035	0.94	8	40%
Micro CHP with improved control	3.19	0.047	0.96	8	47%
Immersion heater	1.36	0.030	0.90	7	80%
Ground source heat pump (1)	1.37	0.039	0.65	10	67%
Ground source heat pump (2)	3.88	0.005	0.59	9	79%

performed when "topping up" this solar hot water system to the 100 L demand benchmark on days when there was not enough sun to deliver this amount of normalised hot water. In the case of the immersion heater this was actually the device used for the purpose. For the other appliances the calculation is a modelling exercise but since all the systems with storage had tanks of similar size and insulation the comparison is reasonable. In all cases it is assumed that this auxiliary heating is controlled such that heat is only applied after the solar panel has had the opportunity to capture whatever solar energy is available.

The top-up energy Q_t consumed each day by an auxiliary system can be estimated as:

$$Q_t = Q_{as}\left(1 - \frac{Q_{so}}{Q_{im}}\right) \quad (4)$$

where Q_{so} is the energy captured that day by the solar thermal system and Q_{as} and Q_{im} are the energy inputs required to produce 100 L from the auxiliary system under consideration and from the immersion system respectively (noting that the same Table 3 model applies to the system shown in Fig. 4 whether the energy input is from solar thermal or immersion). Q_{as} and Q_{im} are adjusted for the actual cold water feed temperature T_c for the time of year by multiplying the values from Table 3 models which assume $T_c = 18\,^{\circ}C$ by $(48 - T_c)/30$.

The results are set out in Table 4. As a sensitivity check given the relatively low output of the solar panel, the effect of scaling up its output by a factor of 2 to 1150 kWh/year is tested, aligning with the median output obtained by EST [20]. Annual carbon emissions are given at current intensity rates and for the electrical appliances the carbon emissions are also calculated using the intensity rate expected for UK grid electricity in 2020 [21]. The table includes for comparison the annual performance of gas "combi" boiler (2) calculated on exactly the same basis but with no solar input (i.e. $Q_{so} = 0$ for every day) since it is not practical to integrate the types of solar thermal panel and instantaneous gas boiler evaluated in this study into a combined system.

5. Discussion

The first point that stands out in considering the results presented in Figs. 9 and 10 is the excellent performance of the combi boilers in terms of efficiency and carbon emissions. Table 3 efficiencies of 76% and 79% are consistent with the overall summer average of 73% reported from 31 boilers by EST [22] although a methodological difference is that EST uplifted heat meter readings by 25% to allow for poor recording of small draw-offs and did not exclude any space heating that occurred whereas no heat meter adjustment was found necessary in the present case (heat meter measurements were checked against separate temperature readings on the hot feed to ensure draw-offs were not missed) and data were scrutinised to exclude space heating. Since combi boilers are forming an increasing proportion of new and replacement gas boiler installations because of the reduced pipework and space requirement by comparison with a conventional system with storage they should provide a useful declining trend in carbon emissions to offset rising hot water use.

The efficiency figures of 40% for the gas boiler and micro CHP systems with storage and simple controls are also consistent with the average of 38% from 10 installations obtained by EST [22] and show the impact of losses from the tank (which are simply a function of the temperature differential between the tank and its surroundings) and the primary circuit (which include pipework, heat exchanger, and combustion losses and occur on every tank heating cycle). These losses are evident in Table 3 either as fixed losses (which comprise tank losses plus some proportion of primary circuit losses) or higher variable costs which cover the balance of primary circuit losses. The figures of 45% and 47% respectively obtained with improved control indicate the benefit of lowering the average tank temperature and also reducing the number of tank heating cycles where possible to 1 per day.

For the electrically heated systems, the striking result is the relatively poor performance of the heat pumps by comparison with the immersion heater. The immersion performs as well or better for households with 1 or 2 occupants. Only at usage levels expected for occupancy of 3 or above does the underlying thermodynamic efficiency of the heat pump become apparent. There are two reasons for this. The first is that the system with the immersion heater gained some benefit from pre-heating of cold water from the mains supply in a loft mounted feeder tank (as did the two gas fuelled systems with storage). It is estimated that this contributes about 4% to the efficiency in Table 3 (i.e. the system would have had an efficiency of about 76% if the tank was fed directly from the mains supply). The second reason is the large number of heating cycles performed by the heat pumps due to the low value for water temperature set point hysteresis of 4 °C employed by the control system. For comparison, the bimetallic strip thermostats used in the gas fuelled systems with simple control had a hysteresis of 10 °C. The effect of this was that the heat pumps performed 4 or 5 heating cycles per day even at low levels of usage, rising to 7–10 per day for usage above 100 L/day. Each cycle incurs losses from the compressor, pipework and heat exchangers which are independent of the amount of heat imparted to the water. In the heating season these losses were reduced because they were partly shared with space heating, but the heat pump COP declined as the ground temperature dropped so the overall efficiency of hot water heating did not change significantly.

The manufacturer's justification for this low hysteresis is the need to avoid affecting users' comfort with a long interruption in space heating while water heating takes place due to the relatively low output power of the heat pump. This is likely to be an increasing constraint because as homes become better insulated under the strategy set out in [2] the power required from the heat pump to meet peak winter demand for space heating will reduce. For overall efficiency it is desirable as noted by studies such as EST [23] and Boait et al. [24] for the maximum power capacity of the heat pump to be matched to the space heat load of the dwelling. The houses

Table 4
Annual performance when providing auxiliary heating to a solar hot water system.

System evaluated	Primary fuel energy input (kWh/year)	CO_2 emissions (kg/year, 2011)	CO_2 emissions (kg/year, 2020)
Gas conventional, 575 kWh solar input	2466	407	
Gas conventional, 1150 kWh solar input	1956	323	
Micro CHP, 575 kWh solar input	2445	404	
Micro CHP, 1150 kWh solar input	1933	319	
Immersion heater, 575 kWh solar input	3187	599	371
Immersion heater, 1150 kWh solar input	2524	474	293
GSHP (1), 575 kWh solar input	3889	730	452
GSHP (1), 1150 kWh solar input	3082	579	358
GSHP (2), 575 kWh solar input	3560	669	414
GSHP (2), 1150 kWh solar input	2715	510	316
Gas "combi" boiler with no solar input	2002	330	

Table 5
Estimated efficiencies with improved tank and primary circuit insulation.

System evaluated with improved insulation	Estimated fixed losses (kWh/day)	Estimated efficiency at 100 L/day
Gas conventional, simple control	1.9	44%
Gas conventional, improved control	1.2	48%
Micro CHP with simple control	4.6	43%
Micro CHP with improved control	2.7	50%
Immersion heater	1.1	85%
Ground source heat pump (1)	0.9	73%
Ground source heat pump (2)	3.3	91%

heated by heat pumps in the present study have winter heat loads of less than 3 kW, so a heat pump with this capacity would take about 40 min to heat a 150 L tank by 10 °C. As an interruption to space heating this clearly could have an impact on users' comfort if it occurred during the day in winter, but might be acceptable overnight while the occupants are asleep. This suggests that variation of hot water hysteresis dependent on time of day and space heating demand could improve hot water production efficiency, but the benefit would depend on the timing and volume of hot water demand.

All the systems with storage would benefit from improved insulation of the tank and primary circuit. Current UK regulations requiring improved insulation of hot water systems [25,26] were not applicable when these systems were installed. These regulations introduced in 2010 specify a maximum heat loss of approximately 1.5 kWh/day from a 100 L tank under conditions specified in [25] and 1 kWh/day from the primary circuit. By comparing these standards with the measured performance of the systems with storage it is possible to estimate the reduction in losses and improvement in efficiency that should be obtained if they were achieved in practice. Table 5 shows the resulting fixed losses and efficiencies indicating potential efficiency gains of between 3% and 12%, with the larger gains attributable to the heat pumps.

The comparison in Table 4 of the primary energy requirements and carbon emissions of the gas and electric fuelled systems when used as an auxiliary heat source to top-up solar water heating shows that the micro CHP with 1150 kWh of solar input in the year provides the best performance at current carbon intensities but by only a small margin over the combi boiler with no solar input at all. The immersion heater has lower energy consumption and carbon emissions under all scenarios than the heat pumps and at the carbon intensity expected for electricity in 2020 delivers lower emissions than the gas fuelled systems. This result based on practical measurement confirms previous findings in purely simulation studies. Thur et al. [27] obtained a similar result favouring use of an immersion heater when comparing solar top-up efficiencies of different appliances. Biaou and Bernier [28] also found that solar thermal production of hot water with immersion top up was preferred as a low carbon water heating solution, when compared to two forms of heat pump and immersion heating alone, with the assumption that photovoltaic panels are used to supply electricity for the heating appliances. Since heat pumps often have an auxiliary immersion heater fitted (with the primary purpose of augmenting the heat pump capacity in extreme winter conditions) this analysis suggests that it should be also be invoked by a suitable control system for water heating whenever appropriate e.g. when the interruption to space heating would be unacceptable or for solar "top up" at higher water temperatures. To gain the full benefit from this proposal the auxiliary heater would need to be immersed in the storage tank rather than operating in the primary circuit as was the case for the evaluated heat pump systems as shown in Fig. 5.

6. Conclusions

The good news for policymakers in the short term is that the established trend for new gas boiler installations to employ instantaneous water heating rather than storage will provide a useful improvement in efficiency and lower carbon emissions as well as lower cost to the consumer. The downside to this trend is that fewer homes will have hot water storage tanks or even space for them to be added. Since a storage tank is essential for solar water heating this may impede the take up of solar thermal systems as incentives for decarbonisation of domestic energy use grow. Also, for an electrically heated home a well insulated hot water storage tank is advantageous because it allows water to be heated at a time when electricity cost and carbon emissions are lowest, so given the long term goal for the UK to use electricity as the primary energy vector [29] the loss of these useful energy stores may be regrettable.

For systems with storage the more rigorous standards for insulation introduced in 2010 should provide a significant improvement in performance as they are applied in practice. However, there is clearly scope to improve control methods so that tank and primary circuit losses are further minimised. Efficiency gains of 5% and 7% from more precise control of temperature have been demonstrated for gas fuelled systems in these limited trials. The heat pumps studied are in particular need of a more adaptive system for thermostatic control of tank temperature that minimises the number of heating cycles while ensuring an adequate level of comfort in space heating – this requirement will be investigated further under the present project. As electricity is decarbonised, the longer term

preferred solution for water heating seems likely to be solar thermal systems with immersion heater top-up, either as an independent subsystem or integrated with a heat pump with "smart" control. The latter option would ensure maximum flexibility to exploit times when cheap electricity is available and allow the heat pump design to be optimised for space heating but retain the capability to contribute to water heating when it can do so efficiently.

Finally, there is clearly some ambiguity in the current published guidance concerning mitigation of *Legionella* in domestic hot water systems. None of the systems studied complied with BS6700 [11], and it is possible that the tendency of most systems with tank storage to give the appearance of compliance by heating some of the stored hot water some of the time to 60 °C results simply in wasted energy with no material reduction in *Legionella* risk while potentially higher risk system components such as loft mounted feeder tanks and shower heads are not addressed. So a realistic assessment of the *Legionella* risks in current domestic hot water systems is needed leading to a revised and consistent set of practical guidelines to which system designers and installers can be expected to adhere.

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