STUDY REPORT

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The Energy Performance of Heat Pump Water Heaters

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Abstract

The energy performance of 11 heat pump water heating (HPWH) systems was examined by installing data logging equipment to the systems. These 11 systems included both integral HPWH systems as well as split system HWPH systems. Three of these systems were from an earlier project examining solar water heating (SWH). The remaining eight systems were part of an audit subspace of a much larger (more than 160 systems), but less detailed, study of HPWH system performance being undertaken by EECA.

The results of the data monitoring showed the performance of the integral HPWH systems was reasonably consistent, although the split systems had varied performance. The three once through split systems performed better than the integral system, and the one recirculating split system performed poorly

Analysis of the energy consumption was made with comparison to the amount of water drawn-off from each system as well as the ambient temperature the units were exposed to. The energy performance of a HPWH system is reduced as the quantity of the water drawn off from the system is reduced or if the HPWH system is operated in a cooler environment.

Acknowledgments

This report was funded by the Building Research Levy.

Data was collected from a number of HPWH systems in conjunction with the Energy Efficiency and Conservation Authority (EECA) as part of a wider evaluation programme.

The help of Eddie Thompson, Martin Garrood and Graeme Howard from EECA is acknowledged.

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1. INTRODUCTION

Water heating is an important residential energy use in New Zealand, accounting for about 29% of total residential energy (Isaacs et al. 2006). New Zealanders have traditionally used moderately performing electrical resistance heating in storage cylinders for their water heating needs (Isaacs et al. 2006). Other more efficient ways of heating water, such as solar water heating (SWH) or heat pump water heating (HPWH), may provide opportunities to reduce New Zealand's residential water heating energy (Pollard 2010) but these technologies are not regularly used. The use of SWH systems in New Zealand has been researched and reported on in a number of reports (Kane, Pollard & Zhao 2007) and (Pollard & Zhao 2008), but HPWH systems have not been subject to much examination.

The range of performance of HPWH systems for different types, brands, time of the year and variation of water use is not well understood. A project funded by the Building Research Levy researched these factors for actual HPWH systems in use in New Zealand houses. This report presents the research that was undertaken and its findings.

HPWH systems are more expensive than traditional water heating technologies but may have a higher energy performance and therefore lower running costs. Financial analysis looks at the balancing of these costs and savings to assess the overall economic viability of these systems for the building owner.

Aspects other than cost savings for HPWH may also be of importance to homeowners;

- the lower ongoing energy costs may provide owners reassurance that future energy bills will be manageable
- the high level of efficiency may provide environmentally conscious homeowners the satisfaction that they are doing their part in reducing carbon emissions
- that the technology is similar to the well-known space conditioning heat pumps which have met with widespread public acceptance in New Zealand (French 2008)
- having a high-performing water heater may increase the resale value of the house.

The greater uptake on HPWH is also of interest to a variety of other stakeholders such as energy companies who need to manage electrical load and demand; the Government which has an interest in improving energy efficiency and in minimising New Zealand's international greenhouse gas emission commitments; and the building and construction industry which needs to ensure new technologies are integrated effectively into our buildings and houses

2. HEAT PUMP WATER HEATING TECHNOLOGIES

The following section provides an overview of the various components of HPWH systems and how they work.

2.1 Heat pumps

A thermodynamic heat pump cycle transfers heat from one reservoir to another reservoir. The evaporator is the heat exchanger located in the first reservoir. This evaporator allows heat from the first reservoir to be transferred to a cold low pressure refrigerant. This warmed refrigerant then enters the compressor which uses electrical energy to mechanically act on the refrigerant to increase its pressure (and temperature) as well as circulating it around to the condenser or the heat exchanger in the second reservoir. The refrigerant loses its heat to the second reservoir across the condenser before the refrigerant is returned to its initial low temperature and pressure state after passing through an expansion valve (see Figure 1)

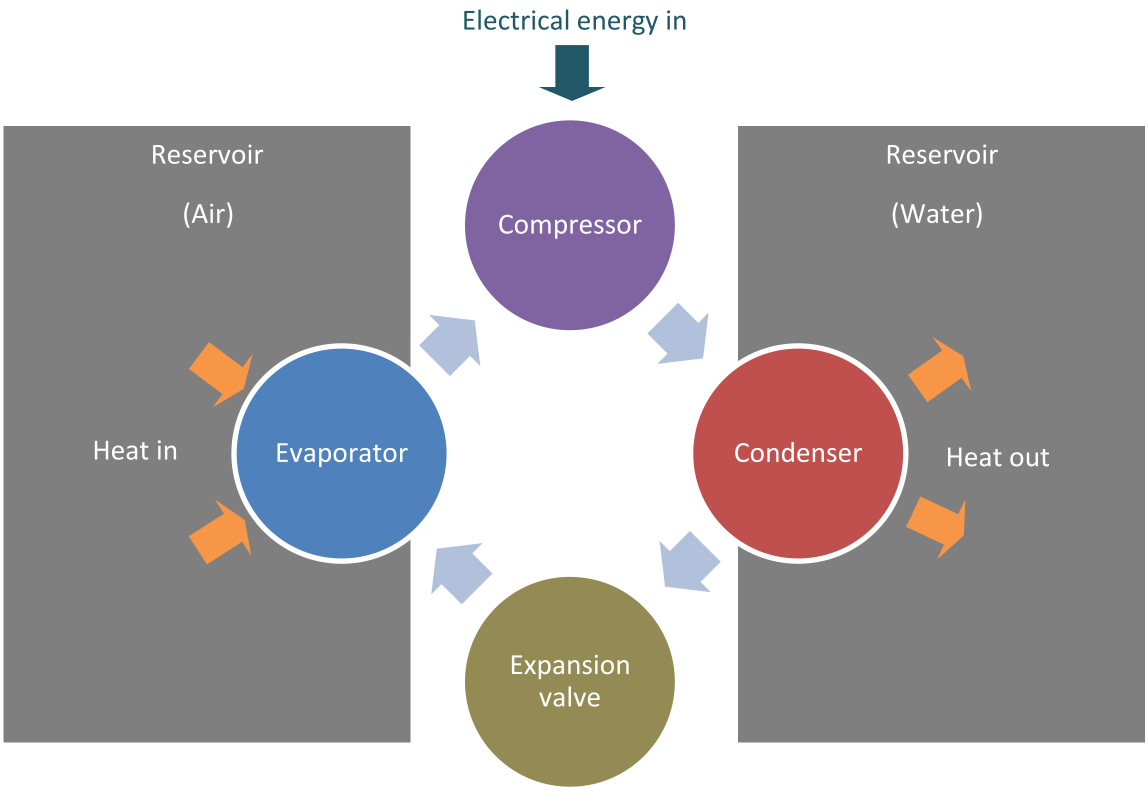

Figure 1. Heat pump thermodynamic cycle

An advantage of the heat pump cycle is that the heat transferred can be much greater than the electrical energy required to drive the cycle.

Household appliances can make use of heat pump cycles. Refrigerators use a heat pump cycle to transfer heat from the air within the refrigerator compartment (thereby cooling it) to the air surrounding the refrigerator.

The appliance commonly referred to as a 'heat pump' (also known as reverse cycle air conditioner) acts on the outside air and the air within a house. For this report these types of heat pumps will be referred to as 'space conditioning heat pumps'. These space conditioning heat pumps generally can operate in either direction: a heating cycle transferring heat from the outside air to the air within the house; or a cooling cycle transferring heat from the inside of the house (cooling the room air down) and delivering it outside.

The refrigerator and space conditioning heat pumps use air as the reservoirs and as such are referred to as air to air heat pumps. Reservoirs other than air can be used, and water and earth are two alternatives. Ground source heat pumps embed pipes in the ground to transfer heat from the more stable temperatures from the ground into another reservoir such as the air within a house. This case would be a ground to air heat pump.

2.2 HPWH systems

HPWH systems are air to water heat pumps. Heat is extracted from outdoor air which is then transferred to water which is then stored within a hot water cylinder.

Unlike most space conditioning heat pumps, HPWH systems do not operate in reverse and are optimised for quite different operating characteristics. Space conditioning heat pump systems typically are required to work between reservoir temperatures of say 5°C outside air temperatures to say 20°C for an inside air temperature. HPWH heaters work between that 5°C outside temperature and a much higher water temperature, usually 60°C.

Increasing the temperature of the output of the heat pump cycle to 60°C is challenging for what can be achieved with systems based on the typical refrigerants used (R-134a). HPWH systems are therefore specifically designed to achieve the necessary water temperature levels. This can be done in several different ways. Some systems continue to recirculate water from the hot water cylinder through the heat pump cycle to transfer additional heat to the water. Other 'once-through' systems complete the heating in one stage taking cold water and producing 60°C hot water for injection at the top of the cylinder. Some systems provide electrical boosting elements inside the hot water cylinder to lift the temperature of the outputted heat pump which may be at say 55°C to the final 60°C storage temperature necessary for Legionella control.

Some HPWH systems incorporate standard hot water cylinders into the system allowing the system to include a separate heat pump unit and hot water cylinder. These systems are commonly referred to as split systems which are different from split space conditioning heat pump systems. In a split space conditioning heat pump system the indoor and outdoor units separate the evaporator and the condenser units from one another. The pipe connections between the indoor and outdoor units of a split space conditioning heat pump system therefore circulates refrigerant. For most split HPWH systems, the outdoor units contain both the evaporator and condenser and water from the condenser is circulated between the outdoor unit and the hot water cylinder.

An integral system packages up the heat pump unit and the hot water cylinder into a self-contained unit. This reduces the amount of plumbing required to install the system. The integral unit needs to be located outside so these types of systems are subject to higher heat losses from having the hot water cylinder located outside as compared to systems where the hot water cylinder is located within the thermal envelope of the house.

Households in Japan use large amounts of hot water and new technology water heaters are popular. High efficiency HPWH systems using CO_2 as a refrigerant are popular with over half a million units sold per year (Meier 2008), despite their high price tag of around NZ$9,000 to NZ$14,000 (Maruyama 2008). These CO_2 HPWH systems are 50% more efficient than models based around a R-134a refrigerant (Meier 2008) and provide water temperatures up to 80°C (Maruyama 2008).

2.3 HPWH performance measures

A HPWH system will have a number of energy flows into and out of the system. A schematic of some of these energy flows is shown in Figure 2. Electrical energy is input into the system to run a heat pump cycle which allows a larger level of environmental heat to be brought into the system to heat water. This heated water is stored and used by the users as required. Storing heated water invariably results in some energy being lost as heat to the surrounding environment as standing losses.

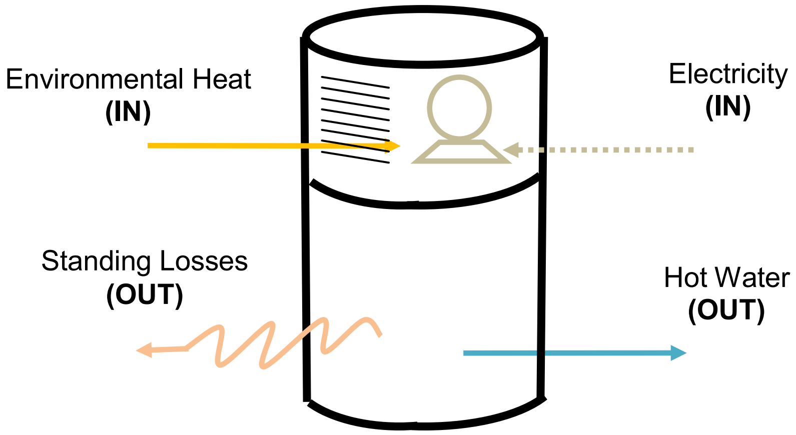

Figure 2. Energy balances of a HPWH system

Figure 3 shows a hypothetical example of an energy balance for a typical HPWH system. The total thermal energy of the system is provided by the output of the heat pump cycle (assuming no electrical heating occurs). This is indicated as the 'Environmental' portion in Figure 3. The electrical load required to generate this thermal energy also appears on the energy sources side (right) of Figure 3. The thermal energy supplies the household with hot water (shown as the 'Draw-off') while an additional amount of thermal energy is lost to the surrounding environment as standing losses from the HPWH system.

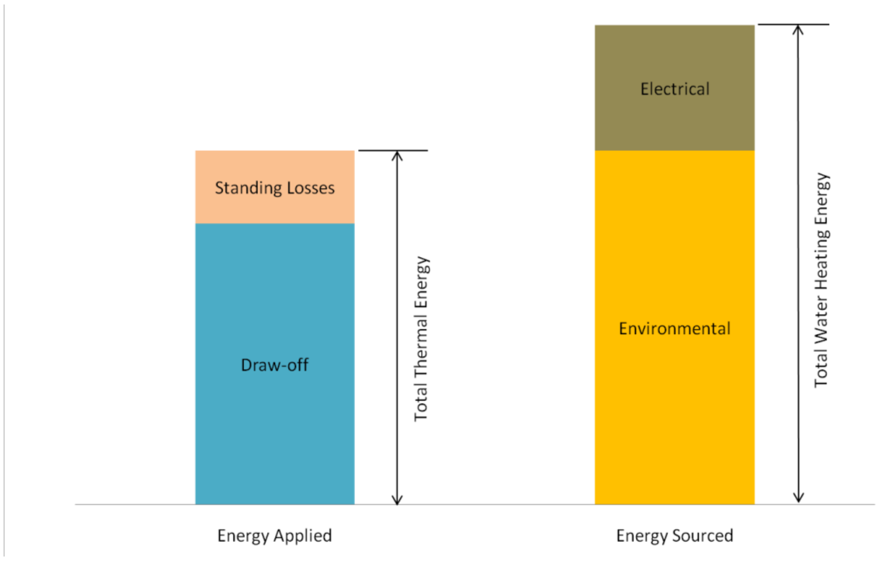

Figure 3. An example of the energy balance of a HPWH system

A well-performing HPWH system will have a low electrical energy input to supply a particular amount of hot water. This will also require that the heat pump cycle provides a good quantity of heat and that the standing losses of the system are small.

Not all of these energy flows are noticeable to the users of the system. What is noticeable is the amount of hot water (taps, showers and baths) that is used, and the electrical input to the HPWH system, which if not separately metered will contribute to the total electrical usage of the household. These, more noticeable, energy flows are shown on the right in Figure 2.

The two energy flows are shown on the left in Figure 2: the environmental heat going into heating the water; and the standing losses of the system which are generally not noticeable to the users of the system. If an alternate design was developed that had an increased level of environmental heat, but also had a similar increase in standing losses, then a certain user would not notice any change in the electrical energy required to operate the system.

Assessing the level of performance should be done on the complete system and not just part of it. The performance of the heat pump cycle to extract heat from the surrounding environment (subject to the electrical input energy) is important, but the effectiveness of the thermal design of the HPWH system also contributes to the overall performance of the system. An example of this partial information is the commonly stated premise that heat pumps can extract up to three units of heat from the surrounding environment for each unit of electricity input. While this may be true, it does not give a complete picture about how well a particular HPWH system may perform.

A difficult energy flow to quantify is the standing losses of the system. The thermal energy losses of the system are dynamic and will depend on varying temperatures within and around the system. Estimations of the standing losses may be possible from examining the performance of the HPWH system when no water is drawn-off from the system.

The overall performance of the HPWH system can be assessed by either considering the HPWH system in isolation and identifying what proportion of the input of the system comes from environmental sources, or by comparing how the HPWH system compares with another type of system such as a typical electrical storage system.

There are a number of alternate performance measures that can be defined and many of these can be defined in subtly different ways (Lloyd & Kerr 2008). One performance measure, known as the coefficient of performance (COP), is a dimensionless ratio constructed from dividing the energy content of the amount of hot water supplied by the system ($Q_{draw\ off}$) by the non-environmental energy or the electrical energy (E_{ne}) used to operate the system.

$$\mathrm{COP} = \frac{Q_{draw\ off}}{E_{ne}} \tag{2.1}$$

An advantage of the COP is that the parameters can be readily determined and it does not require an estimate of the standing losses for the system to be calculated. This improves the accuracy of the estimate, but requires more care when interpreting its values. An instantaneous electric water heater would have a COP of 1 as 100% of the electrical energy input is converted to heated water for the users. An average storage hot water cylinder, however, has standing losses of around 33% of the total water heating energy (Isaacs et al. 2006). These standing losses lead to a COP for an average electric storage cylinder of 0.67. A system with a COP of 1.34 would therefore require half as much water heating energy as a standard electric storage cylinder for a given amount of hot water.

2.4 Current performance information

Performance information on HPWH systems can be obtained from experimental testing, modelling or actual in-use testing.

Experimental testing involves controlling or monitoring the ambient environment the HPWH system is exposed to and scheduling draw-offs of hot water throughout the testing period. Experimental testing provides results that can be verified and reproduced. The results can also be used to rank and compare different HPWH systems.

There is no currently accepted test method but one is under current development in draft Australian/New Zealand standard AS/NZS5125 (SNZ 2009). While undertaken using different testing methodologies Table 1 provides a range of experimental results from three separate studies.

Table 1. New Zealand experimental studies of HPWH performance

Source	Range of COPs
Carrington et al. 1984	2.4 – 3.0
Lloyd and Kerr 2007	1.6
Whitley 2009	1.2 – 3.0 (125 L/day, take COP_{ref} =0.8)

Experimental testing is time-consuming and expensive. A change to part of a system may require a complete new experimental test to be undertaken to provide new performance information for the modified system. An alternative to experimental testing is to undertake limited component testing and to use a comprehensive computer model to estimate the operating performance of the complete system.

TRNSYS (University of Wisconsin 2010) is the preferred computer program to undertake this modelling. AS/NZS 4234:2008 is a standard for modelling the energy performance of water heating systems (SNZ 2008), which details how this modelling should be undertaken. AS/NZS 4234:2008 is currently being amended to incorporate HPWH systems.

Modelling has the advantage that performance variations can be easily examined from a base model. A disadvantage of modelling is that it requires detailed information on how much and when the occupants use water.

Actual in-use testing of HPWH systems involves the measurement of system characteristics as it is being used in an actual setting. The variations of time of use, quantity of water used, temperatures and system operation all contribute to more uncertain results. Actual in-use testing, however, shows more accurately what might be achieved in practice and complements experimental testing and modelling.

Carrington et al.(1984) undertook tests on seven HPWH systems installed in households in Dunedin and Auckland. Lloyd and Kerr (2008) estimated the equivalent COP for these actual systems ranged from 1.1 to 1.7, which is somewhat below the experimental performance.

3. DATA COLLECTION

Data for this project came from two sources. One was the continued monitoring of HPWH systems participating in a previous SWH / HPWH project (Pollard & Zhao 2008). This data set included three systems monitored for one year. The other data source, which provided eight systems, was from an audit subsample of an EECA project (EECA 2009).

The EECA project involved a grant of $1000 for newly installed HPWH systems providing they also installed a water meter and electricity (both supplied by EECA) and that the occupants provided meter readings for three months. Approximately 160 households participated in this project and provided meter readings.

In order to provide more comprehensive data to allow specific issues to be examined, EECA selected a smaller (22 systems) audit subsample to which BRANZ data monitoring equipment (shown in green in Figure 4) was added. This additional monitoring equipment allows the operation of the HPWH system to be better understood and the performance of the system to be more accurately assessed. Many of these systems monitored in the audit subsample had water meters mis-positioned, excessive missing data or were used in a non-residential setting and were therefore excluded from this analysis. Overall eight of the systems are included.

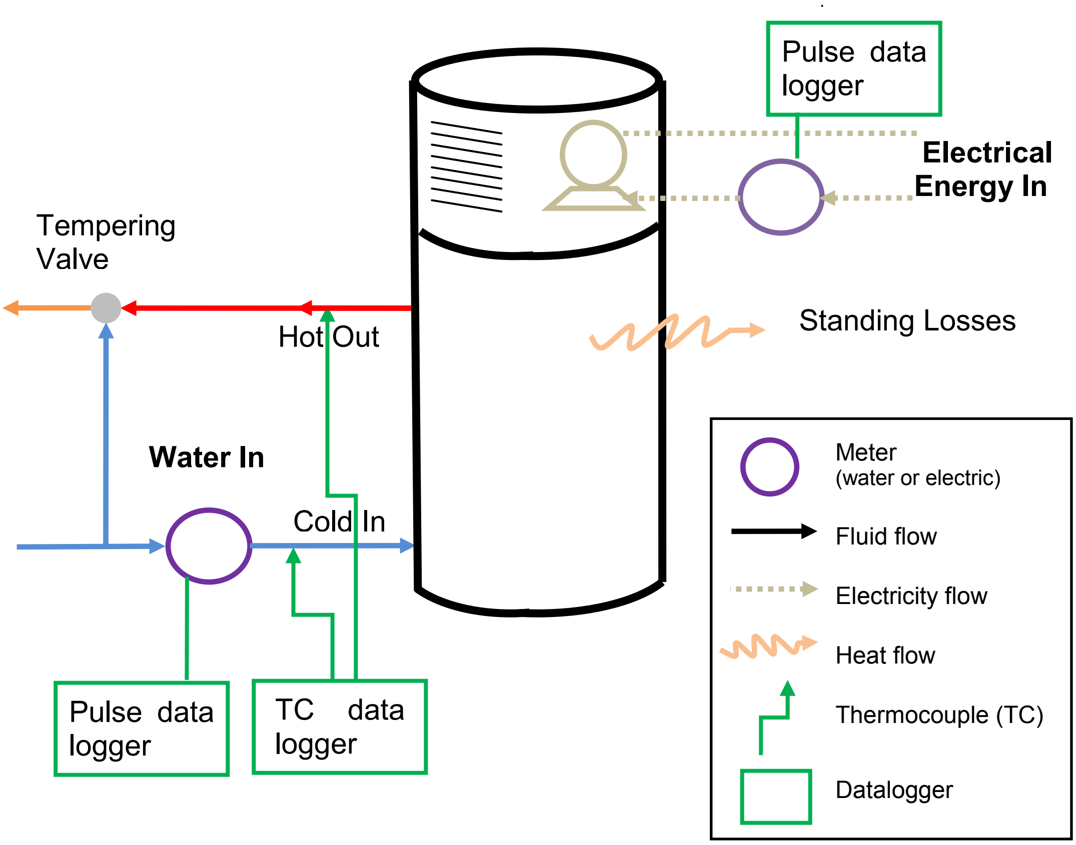

Figure 4. Monitoring arrangement for each HPWH

4. RESULTS

Table 2 gives details of the HPWH systems examined. Systems 1, 2 and 3 were systems from an earlier project (Pollard & Zhao 2008) and were previously identified as systems H36, H37 and H38 but now with a year's worth of data. It was noted in Pollard and Zhao (2008) that H37 was not operating correctly. This system was repaired by the distributor and the data used for this project is only the data collected after this system was fully operational.

Systems 4-11 were taken from the EECA HPWH audit subsample of those systems which had sufficient data, and which had the water meter installed after the take-off branch so that the draw-off energy could be calculated accurately.

The systems were located in either Auckland or Wellington and were monitored for at least 151 days. The HPWH systems were of a number of types: integral, split (once-through) and split (recirculated).

The consumption figures of water use and electrical energy in Table 2 were calculated by extending the available data for that particular measure to determine an annualised estimate.

Table 2. HPWH system details and daily water and annual electrical use

System	Type	Location	Days	Average water use (Litres / day)	Electrical energy (kWh / year)
1	Integral	Auckland	365	138 ± 2	1520 ± 15
2	Integral	Auckland	365	43 ± 1	904 ± 9
3	Integral	Auckland	365	100 ± 1	1480 ± 15
4	Split- once thru	Auckland	249	117 ± 2	940 ± 9
5	Split- once thru	Auckland	180	91 ± 2	823 ± 8
6	Integral	Auckland	181	213 ± 4	1200 ± 12
7	Split- once thru	Auckland	151	246 ± 5	1520 ± 15
8	Integral	Auckland	182	126 ± 3	1370 ± 14
9	Integral	Wellington	298	144 ± 3	1770 ± 18
10	Integral	Wellington	239	365 ± 7	2900 ± 29
11	Split – recirc.	Wellington	220	90 ± 2	2250 ± 23

4.1 Water use

In comparing two HPWH systems using an experimental or modelling approach, the same quantity of water and water draw-off pattern is used for both systems and the system with the lower electrical energy use would be identified as the better system.

Comparing two HPWH systems in actual use is more difficult. The two sets of occupants will almost certainly use different amounts of water and may use water at different times of the day (usage patterns). Increased water use will require increased electrical energy use. Operating an alternate usage pattern will result in a different energy use, but the change will be of a smaller size than from changing the quantity of water used. Bourke and Bansal (2010) examined an alternate usage pattern from the standard profile used in AS/NZS 4234:2008 and found that overall energy use differed by up to 12%.

Figure 5 gives an example of the energy consumption of two HPWH systems established from actual use. The lower blue line is a well-performing HPWH system using less energy than the other HPWH system, shown as the red upper line for a given level of water usage. It may still be the case that the well-performing system uses more energy than the other system if its water use is higher. The two points shown on the curves are such cases.

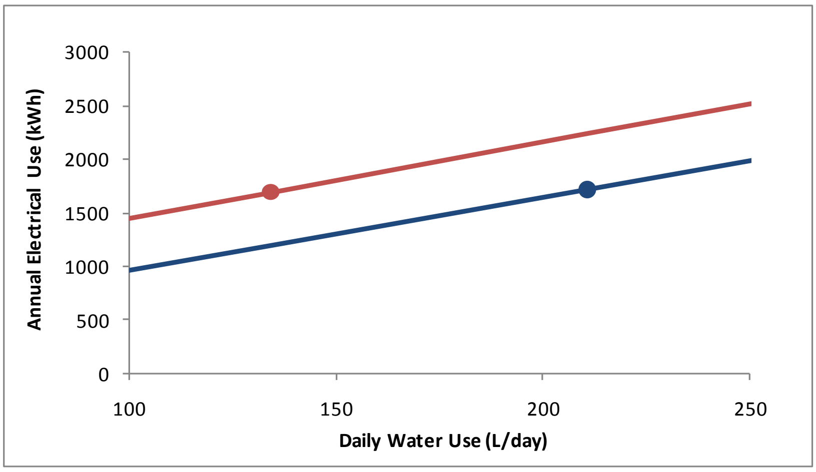

Figure 5. Example of the performance of two HPWH systems

Box plots of the daily water use for the 11 HPWH systems are shown in Figure 6. The lower edge of the box separates the bottom 25% of values, while the top edge of the box separates the top 25% of values. The median value is shown as a bar across the box. These box plots are arranged in order of increasing median water usage. The orange lines show levels for the mid points between the very small, small and medium draw off levels which are defined in Table 3. The small, medium and large draw-offs approximately align with the corresponding levels from AS/NZS4234:2008.

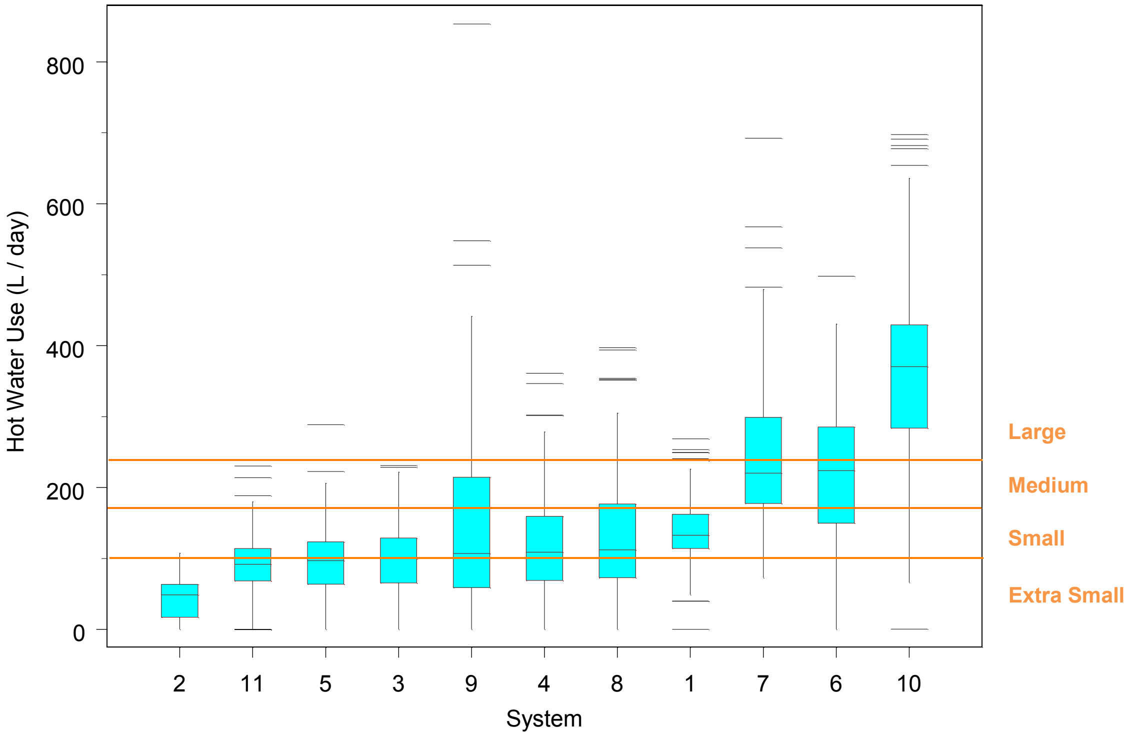

Figure 6. Box plots of the daily water use for each of the HPWH systems

Table 3. Hot water usage levels

Description	Draw-off energy		Approximate† draw-off volume
	(MJ/day)	(kWh/day)	(L / day)
Extra Small	*12.2*	*3.4*	*65*
Small	25.6	7.1	136
Medium	39.0	10.8	207
Large	52.0	14.4	276

† The volume of water drawn-off is calculated assuming that the outlet water is 60°C and the inlet water is 15°C

Many of the households had low water use. Table 4 gives the proportion of the daily water use within each interval for each HPWH system. Those HPWH systems in Table 4 whose proportion within an interval was less than 10% are shown with red shading. Eight of the 11 households had daily draw offs more often in the small and very small intervals rather than in the medium and large intervals. Information on the number of occupants usually present within each household was not available.

Table 4. Proportion daily water use is within a particular range (red shading indicates less the 10% of the time)

System	Daily Water Use (L / day)			
	<100 *(very small)*	100-171 (small)	171-241 (medium)	>241 (large)
2	0.984	0.016	0.000	0.000
11	0.589	0.380	0.031	0.000
5	0.525	0.433	0.035	0.007
3	0.504	0.427	0.068	0.000
9	0.481	0.191	0.137	0.191
4	0.442	0.347	0.171	0.040
8	0.408	0.326	0.168	0.098
1	0.150	0.656	0.183	0.011
7	0.021	0.176	0.366	0.437
6	0.127	0.193	0.307	0.373
10	0.012	0.047	0.076	0.866

A histogram of the average daily water use for 28 SWH systems taken from Pollard & Zhao (2008), together with the 11 HPWH systems examined in this project is shown in Figure 7. While the sample size of 39 systems is small, the distribution appears to have a long tail. Water use therefore may not be well represented by average water use as many systems may have water use much higher than average.

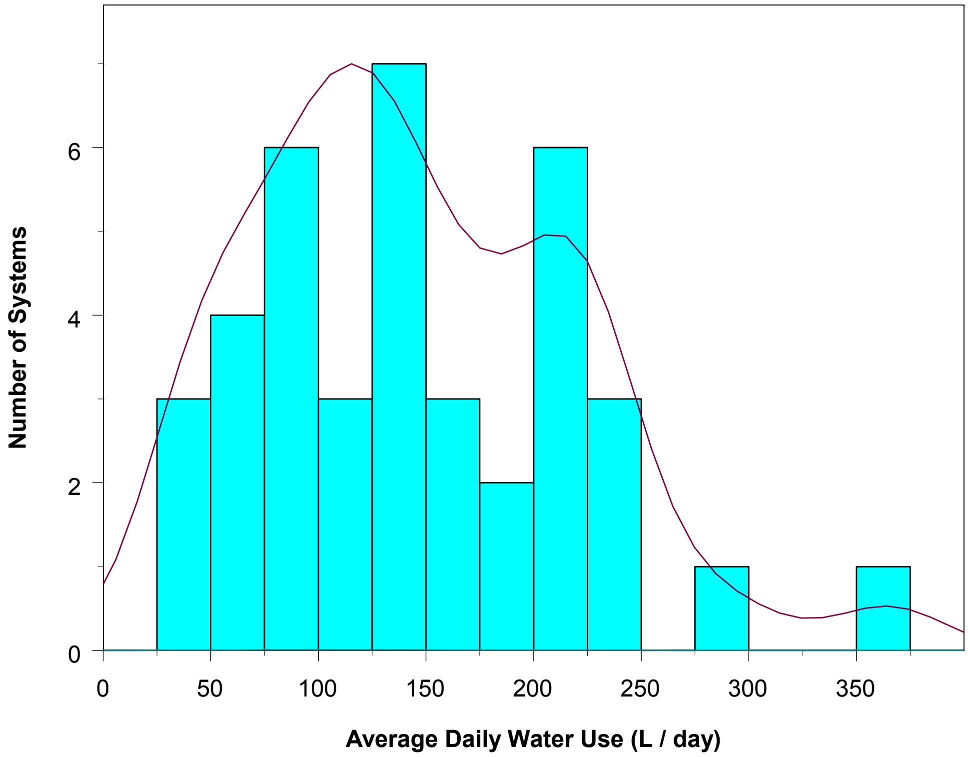

Figure 7. Histogram of average daily water use for 28 SWH systems, taken from Pollard and Zhao (2008) and the 11 HPWH systems examined in this project

4.2 Water temperatures

In order to calculate the COP for a HWPH system from equation 2.1, the energy content of the hot water drawn off from the cylinder is required. This draw-off energy content is calculated as follows

$$Q_{draw\ off} = \rho V c(T_h - T_c) \tag{4.1}$$

Where

ρ Is the density of the water drawn-off

V Is the volume of the water drawn-off

c Is the specific heat capacity of water

T_h Is the temperature of the water drawn-off

T_c Is the temperature of the incoming cold water

The temperature of the draw-off water (hot) and the incoming water (cold) was measured by connecting a thermocouple to the outside of the copper pipe approximately 300 mm from the outlet. Table 5 gives the average and standard deviations for these temperature measurements when the water is drawn-off from the hot water cylinder. There is a delay for the pipe to warm up as water passes through it, so the temperature measurements were delayed one time interval (six minutes) to more accurately reflect the temperature of the water at that time.

Table 5. Hot water temperature, cold water temperature and their difference at times of water draw-off

System	Hot water temperature (°C)	Cold water temperature (°C)	Temperature difference (°C)
1	56.0 ± 2.8	19.0 ± 4.5	37.1 ± 5.0
2	52.9 ± 1.9	18.8 ± 3.7	34.1 ± 3.8
3	54.1 ± 2.9	15.6 ± 3.9	38.5 ± 4.9
4	53.3 ± 2.8	19.1 ± 3.6	34.2 ± 4.2
5	53.5 ± 2.5	17.7 ± 3.4	32.6 ± 2.6
6	56.7 ± 2.8	17.0 ± 1.7	37.4 ± 2.9
7	53.3 ± 4.5	21.9 ± 4.3	29.6 ± 5.3
8	54.7 ± 2.3	15.6 ± 3.1	39.1 ± 3.6
9	51.7 ± 3.6	17.7 ± 1.5	34.0 ± 3.5
10	53.4 ± 3.5	15.3 ± 4.0	38.1 ± 6.7
11	51.6 ± 2.0	17.7 ± 2.0	32.4 ± 3.2

While the method of measuring the temperature may not accurately reflect the temperatures within the hot water cylinder, all of these temperatures are lower than the 60°C required for effective Legionella control. Two of the three systems in Wellington had average hot water temperatures at the time of hot water draw-off lower than 52°C, which was lower than the all of the Auckland systems.

The average temperature difference between the hot and cold water ranged from 29.6°C to 39.1°C. Overall a pooled estimate of the average temperature difference for all of the systems was 36.3 ± 5.2 °C.

4.3 Coefficient of performance

The measured draw-off energy and measured COP along with estimates of their measurement uncertainties are given for each of the systems in Table 6. The water meters for systems 1-3 were more accurate (1.5% rather than 2%) and better resolved (0.03 L rather than 0.5 L) than the meters used for Systems 4-11, allowing the performance for Systems 1-3 to be more accurately determined.

Also shown in Table 6 is a calculated COP for each of the HPWH systems. This value is calculated from the annual estimate of the hot water volume multiplied by an assumed temperature difference of 36.3 °C (the pooled estimate from section 4.2), the density of the water and the heat capacity of the water. This product is then divided by the annual electricity usage of the HPWH system to arrive at the calculated COP.

Table 6. Draw-off energy, measured COP and COP calculated from meter readings

System	Draw-off energy (kWh / year)	Measured COP	Calculated COP (T_d = 36.3 °C)
1	2290 ± 53	1.50 ± 0.05	1.4 ± 0.2
2	632 ± 14	0.70 ± 0.02	0.7 ± 0.1
3	1710 ± 43	1.16 ± 0.04	1.0 ± 0.2
4	1690 ± 69	1.80 ± 0.08	1.9 ± 0.3
5	1430 ± 48	1.73 ± 0.07	1.7 ± 0.2
6	1970 ± 120	1.63 ± 0.11	1.7 ± 0.3
7	2850 ± 120	1.88 ± 0.09	2.5 ± 0.4
8	2850 ± 130	1.50 ± 0.10	1.4 ± 0.2
9	2020 ± 130	1.14 ± 0.08	1.3 ± 0.2
10	5800 ± 330	2.00 ± 0.12	1.9 ± 0.3
11	1190 ± 34	0.53 ± 0.02	0.6 ± 0.1

In most cases, the simplified calculated COP is close to the more accurate measured COP, which can be seen in Figure 8 as it compares these two measures. The system with the biggest difference between the calculated and measured COPs is System 7. System 7 had an average temperature difference between the hot and cold temperatures of only 29.6°C, smaller than the assumed difference of 36.3°C used in the calculation. This lower actual temperature difference has the impact of over estimating the calculated COP.

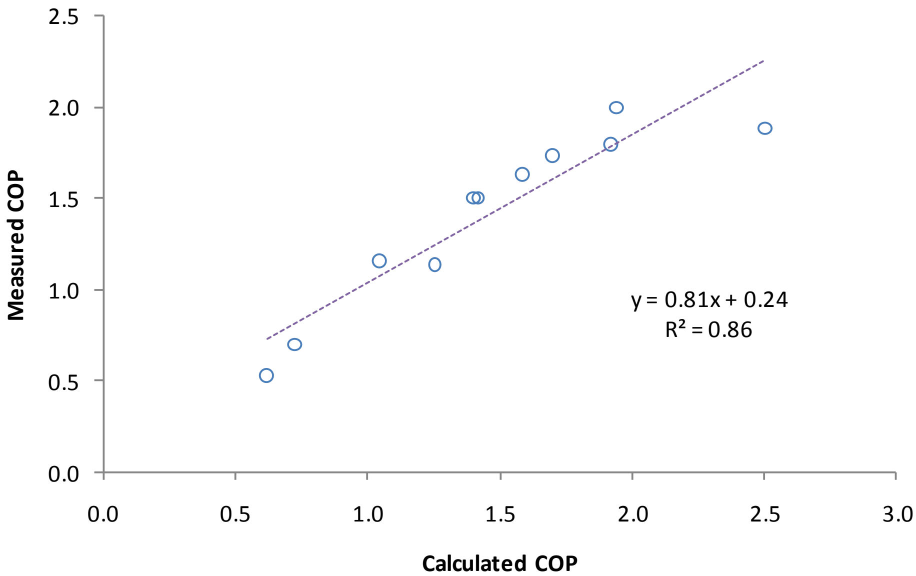

Figure 8. Comparison of the calculated COP and measured COP for the HPWH systems

The calculated COP can be determined solely from readings of the water meter and electricity meters. This avoids the need for data loggers to automatically collect the meter readings and to measure the hot and cold water temperatures that are necessary to determine the measured COP for a particular system.

4.4 Linear regression of daily energy use

It is difficult to compare the performance of different HPWH systems from single measures such as the calculated COP, the measured COP or the electrical energy use. These performance measures are dependent on a range of factors such as the amount of hot water used, the ambient and cold water temperatures and the relative humidity level.

Where data loggers have been used, it may be possible to divide the data into separate analysis intervals (single days) and use measured values of these influencing factors to examine their relationship with the performance measures as part of a linear regression model.

Linear regression models were constructed for the daily electricity consumption for each of the HPWH systems. In addition to the water use information (both the daily volume of water used and the daily thermal energy draw-off), climate information for both Auckland (Khyber Pass, NIWA Agent 22164) and Wellington (Kelburn, NIWA Agent 25354) was sourced. This climate information was from NIWA's Cliflo database (NIWA 2005) and included the dry bulb temperature, the wet bulb temperature, the relative humidity and the dew point temperature.

The factors contributing to the model were assessed. The simple measurement of the daily water volume provided a good correlation with the daily energy use, although the daily draw-off energy provided a better correlation. Determining the daily draw-off requires a series of calculations, and that information was available so draw-off energy was used as a regression parameter.

The outdoor dry bulb temperature also had a good correlation with the daily energy use and was combined with the daily draw-off energy to provide a two-parameter regression model.

Experimental work (Morrison, Anderson & Behnia 2004) has shown that the humidity conditions are important. Both the daily average wet bulb temperature and the daily average dew point temperature provided good correlations with daily energy use. However this is as a result of both of these factors being highly correlated with the average dry bulb temperature. When added in turn to the two parameter regression model they provided little additional information to the model.

The daily average relative humidity is not correlated with the dry bulb temperature, nor does it correlate to the daily energy use. Adding the relative humidity to the two-parameter regression model provided little additional information to the model. While the humidity may be a contributing factor to HPWH performance, its role in these cases is masked by the other parameters.

The two-parameter regression model provided good fits for 10 of the 11 HPWH systems examined. System 5 did not fit the data well, producing coefficients with opposite signs to the other models. System 5 had a high degree of missing data for the hot water temperatures which also affected the draw-off energy and measured COP. The regression results for System 5 have been excluded from this section.

The regression results for the two-parameter model were examined by fixing the draw-off energy to the small level (7.1 kWh / day) and by varying the outside temperature from 3°C to 21°C. Figure 9 shows curves of the modelled COP for each of the 10 available systems. As the temperature is lowered the performance of the HPWH system decreases. The integral systems are bunched together in the centre of the graph while the two once-through split systems have a higher modelled COP. At higher temperatures these two once-through split systems are close together, but separate as the temperature is reduced. The one recirculating split system has a lower modelled COP.

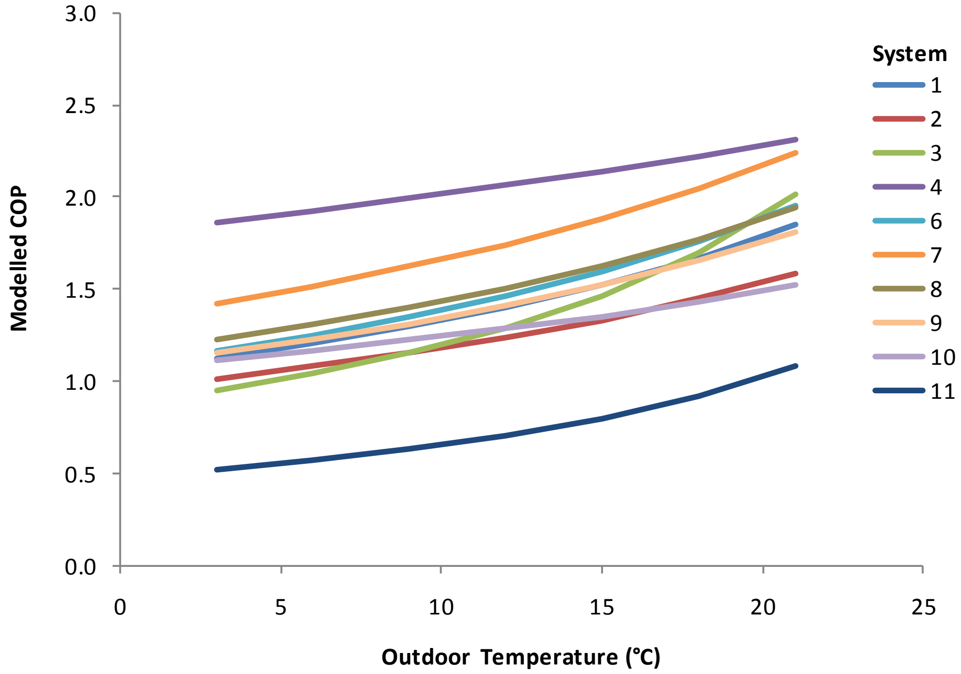

Figure 9. Dependence of the modelled COP on the outdoor temperature for a small draw-off

At 15°C the average daily electrical energy input to the 10 systems was 5.0 kWh. When the temperature was lowered to 6°C the average daily electrical energy for the 10 systems increased 27% to 6.3 kWh.

Two big drivers of changing outdoor temperatures are the change from summer to winter for a particular location and changing the location to a warmer or cooler part of the country. The first is important for how well a HPWH system will perform year round, the second is important to ensure that the technology is suitable for that part of the country. Both of these drivers were therefore examined using the data collected.

Table 7 gives a comparison of the modelled average electrical energy input to the 10 HPWH systems for a small draw-off subject to a variety of outside temperatures. These temperatures were selected to match the January and July temperatures in seven centres throughout New Zealand and were sourced from NIWA data for 1971-2000 (NIWA 2010). The ratio of winter energy use to summer energy use was around 1.26-1.27 for most centres. Christchurch, which has a more extreme climate (warmer summers and cooler winters), had a ratio of 1.35. Hamilton, which also has cooler winters, had a high ratio of 1.32.

Table 7. Modelled change of energy use between January and July

Centre	Average January temperature (°C)	Average July temperature (°C)	Change in energy use
Kaitaia	19.7	12.2	1.27
Auckland	19.3	11.6	1.27
Hamilton	18.3	8.7	1.32
Wellington	16.9	8.8	1.26
Christchurch	17.4	6.6	1.35
Dunedin	15.2	6.5	1.27
Invercargill	14.0	5.2	1.26

Table 8 shows the average modelled energy use for the 10 systems relative to Auckland. The range of average energy use for the systems modelled in Invercargill was 18% higher than the average energy use for the systems modelled in Kaitaia.

Table 8. Modelled energy use relative to Auckland

Centre	Average temperature (°C)	Energy use relative to Auckland
Kaitaia	15.7	0.98
Auckland	15.1	1.00
Hamilton	13.7	1.04
Wellington	12.8	1.07
Christchurch	12.1	1.09
Dunedin	11.0	1.13
Invercargill	9.9	1.16

The other parameter of the regression model was the draw-off energy. For this analysis, the outside temperature was fixed at 15°C and the results of the regression were examined by varying the draw-off energy. Figure 10 shows the resulting COPs for each of the modelled systems for a range of draw-off energies. As linear regression is a fitting procedure it is important to limit the range of input water draw-offs to a similar range over which the model was fitted so that predictions are not extrapolated beyond the data. It is seen in Table 4 that many of the systems only operated over a limited range of water draw-offs. The COP curves in Figure 10 have been limited to those draw-off intervals which were used for more than 10% of the time.

Again the integral systems appear close together in the middle of the graph. The two once-through systems have higher performance but are less consistent in their operation. The recirculating system (System 11) has a lower performance for the extra small and small draw-off ranges over which it operated.

As the water draw-off decreases, the COP decreases. With increasingly lower water draw-offs, the standing losses of the systems become a far more important component in the energy use of each system. Many of the hot water cylinders were located outside, subjecting the hot water inside the cylinder to a higher heat loss to the ambient environment.

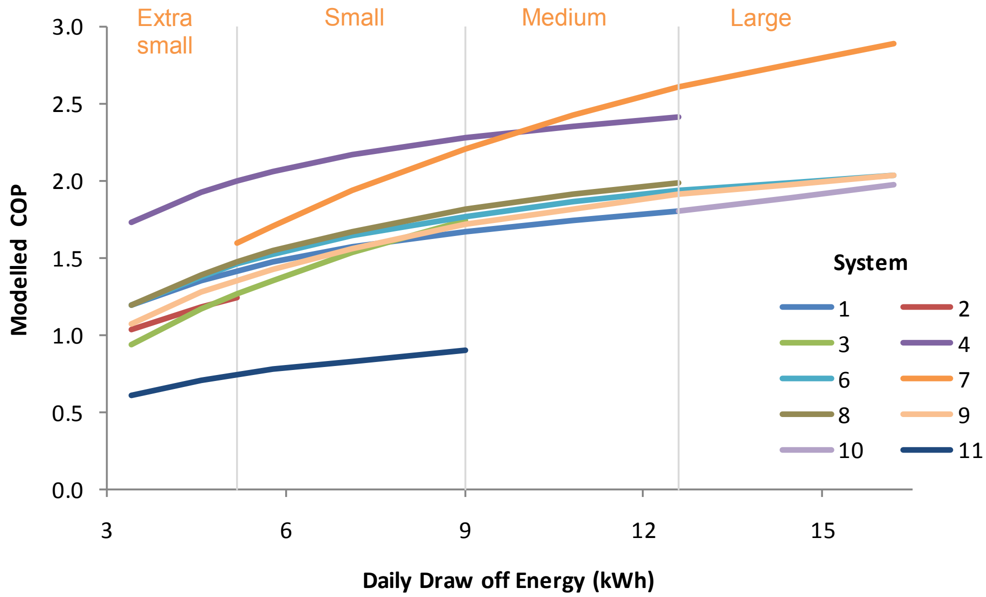

Figure 10 Dependence of the modelled COP on the quantity of hot water draw off

Excluding the two systems which had little extra small use (Systems 7 and 10) the remaining eight systems had an average COP of 1.61 for a small draw-off (7.1 kWh) at 15°C. These same systems had an average COP of 1.14 or 41% lower when an extra small (3.4 kWh) hot water draw-off was used in the regression model. It was seen in Table 4 that the very low water draw-off was a popular operating mode.

This analysis has shown that it is important to consider the energy draw-off when assessing a COP results. From Table 2 it was seen that System 2 had a low COP of 0.7 but also had a very low hot water use averaging 43 L/day. As System 2 had only small usage, the curve for it shown in Figure 10 (coloured red) only covers the low usage but is at a similar level to other integral systems.

5. DISCUSSION AND CONCLUSIONS

The results of the data monitoring showed the performance of the integral HPWH systems was reasonably consistent, although the split systems had varied performance. The three once-through split systems performed better than the integral systems, and the one recirculating split system, which performed poorly, not exceeding 1 over the extra low and low ranges it operated over. In order to give consumers confidence that all systems perform well, HPWH performance testing should be standardised and information made available to consumers.

The performance of a HPWH system is reduced when daily water draw-off is low. In order to ensure a reasonable level of performance (a COP of 1.5) is achieved by a typical HPWH system the hot water demand for the household should be at least 140 L per day. Seven of the 11 households examined had average daily hot water usage of less than 140 L per day. Consumers should be made aware of the lesser performance of HPWH systems when water use is low to allow them to make informed choices.

HPWH systems are also affected by the external temperature and would have increased energy use in winter as compared with summer. Some models of HPWH systems are only suited to warmer areas such as the North Island (excluding the volcanic plateau). The year-round performance of a HPWH system in Invercargill would be around 14% less efficient than an equivalent system in Auckland.

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