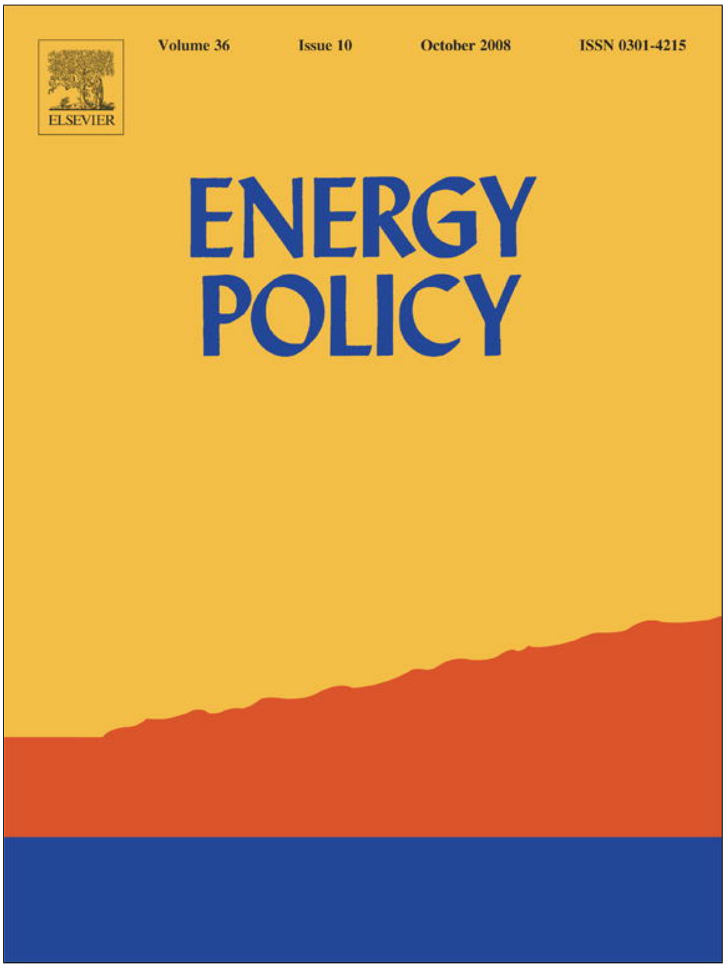
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Performance of commercially available solar and heat pump water heaters

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ABSTRACT

Many countries are using policy incentives to encourage the adoption of energy-efficient hot water heating as a means of reducing greenhouse gas emissions. Such policies rely heavily on assumed performance factors for such systems. In-situ performance data for solar and heat pump hot water systems, however, are not copious in the literature. Otago University has been testing some systems available in New Zealand for a number of years. The results obtained are compared to international studies of in-situ performance of solar hot water systems and heat pump hot water systems, by converting the results from the international studies into a single index suitable for both solar and heat pump systems (COP). Variability in the international data is investigated as well as comparisons to model results. The conclusions suggest that there is not too much difference in performance between solar systems that have a permanently connected electric boost backup and heat pump systems over a wide range of environmental temperatures. The energy payback time was also calculated for electric boost solar flat plate systems as a function of both COP and hot water usage for a given value of embodied energy. The calculations generally bode well for solar systems but ensuring adequate system performance is paramount. In addition, such systems generally favour high usage rates to obtain good energy payback times.

1. Introduction

Solar hot water systems are seen as one step in moving towards a future of self-sufficiency in energy supply. Recent criticisms, by Monbiot (2007) among others, of the trend to replace traditional consumption with "green consumption" of energy-efficient products, however, are emerging and warrant that a careful performance analysis be completed for such products before declaring that they will contribute to saving the planet from resource depletion and global warming (Lloyd, 2007). Certainly solar systems permanently connected to electric boost supplies, which typically give between 30% and 70% electricity savings, can be criticized on the grounds that reducing hot water consumption by between 30% and 70% will give the same overall energy savings, for no outlay in terms of cost or embodied energy. Similarly, installing energy-efficient products of any kind will not produce total energy savings while population rises and the number of such products continues to grow. Energy-efficient hot water systems are most useful if the population does not wish to cut down consumption, instead favouring improved technology to deliver benefits. Such a strategy only works, however, in a situation whereby the rate of new adoption is relatively low. This paper analyses existing data together with some data of our own to give some bounds on the expected performance of solar and heat pump hot water systems.

Performance testing of solar hot water systems and heat pumps has been carried out for many decades, peaking in the 1980s. Unfortunately, much of the testing has been on the absorber panel performance and the heat pump module and in ideal conditions rather than on long-term whole system performance where the vagaries of the consumer and the weather are taken into account. In particular, the interaction of the active system with the storage system has not been extensively documented.

Shariah and Ecevit (1995) noted for thermo-siphon systems that "Generally the performance of the thermo-siphon system is given in terms of the instantaneous efficiency on clear days. However, this does not give the true long-term performance of the system because of varying climatic and radiation conditions". In terms of the user interaction, Prud'homme and Gillet (2001) suggested that current control strategies for solar hot water systems "do not take into account the evolution of the operational conditions, typically the users' needs in terms of draw off and the weather conditions". Importantly, the implementation of control strategies to manage the electric boost that is typically used on many systems has not been a high priority by either system designers or manufacturers. The priority has been on maximizing energy transfer from solar radiation to the storage tank on a given

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day. The theory at least is that provided there is good thermal stratification in the storage tank, and the boost element and the thermostat are placed between half way and a third of the way from the top of the tank, then the energy from the boost element will not interfere with solar collection.

Unfortunately, there is some evidence that satisfactory thermal stratification may not be always achieved in practice. Jordan and Furbo (2005) note that the stratification depends "on the flow rate the draw off volume as well as the initial temperature in the storage tank". Other factors include the orientation of the tank (either vertical or horizontal), the presence of an effective diffuser on the cold water inlet, the flow rates for circulating pumped systems and the geometry and configuration of the boost element. With little or no thermal stratification, a solar hot water system utilising a simple thermostat control is likely to perform badly, particularly when draw off occurs either in the evening or early morning, as the boost will turn on and heat the water in the storage tank by the time the sun is high enough in the sky to allow solar collection. Shariah and Lof (1997) looked at four different daily consumption profiles and found that when water was drawn off during the evening and morning the efficiency of the system was reduced. They also found that randomly timed draw offs over a 24 h period gave the best overall system performance. It should be noted here that if solar collector panels are retrofitted to existing storage tanks it is unlikely that the positions of the control thermostat, panel return line, the boost element or the cold water intake diffuser can be modified to optimally suit solar energy collection.

There are two ways of overcoming the problem of poor storage tank configuration. One is to physically modify the storage tank and booster element arrangement to reduce mixing of hot and cold water; the other is to control the timing of operation of the boost element so that priority is given to solar heating. Solutions relying on reconfiguration can be complex and involve separation of the storage tank into separate compartments or separate tanks (Ragoonanan et al., 2006), resizing or relocating the element inside the tank and resizing or relocating the element outside the main tank. In the latter case, the solar system acts as a preheater for an instantaneous electric (or gas) heated system as the boost heater will have no storage attached. All these solutions have been proposed and implemented but they rely on a remanufactured system. Controlling the timing of operation of the boost element can more easily be applied to existing systems with little if any re-engineering. The control system may be a simple on–off timer or a more sophisticated intelligent device that can account for consumer behaviour and weather patterns. Prud'homme and Gillet (2001) have proposed optimising a system including both re-engineering the storage tank configuration and by implementing advanced control strategies, including obtaining weather forecasts and automatic prediction of user water draw off. Dennis (2002) has also presented an "advanced control solution to allow the thermostat to operate with discretion so that less solar energy is displaced by the operation of the auxiliary heater".

In terms of net energy analysis, Crawford and Treloar (2004) calculated the energy payback time for solar hot water systems in Australia their conclusions were that the systems provided a net energy savings compared to conventional systems after 0.5–2 years, for electric- and gas-boosted systems. Their paper, however, did not take into account the wide variation in performance of systems or the amount of hot water actually used.

2. Methodology

The overall performance of a solar or heat pump system that is permanently connected to a (main or backup) non-environmental energy supply can be represented by a variety of indices including the solar fraction and coefficient of performance (COP). As the COP is the preferred quantifier for heat pump systems it will be used here, with comparisons to other representations. The other reason for using COP is that this quantifier does not depend on the efficiency of a standard (usually electric) system as is for the case of quantifiers that incorporate energy saved, for instance. In addition, the boost energy in the COP calculation need not be electricity and other sources such as gas or oil could also be substituted. Because of the non-standard approach use in the literature to delineating the performance of solar and heat pump systems a systematic method of comparison is needed. This comparison is presented below.

The COP for a solar thermal system is defined as the ratio of the thermal energy (referenced to the actual input water temperature) drawn off from the system (Q_{useful_load}) to the non-environmental boost energy input, E_{ne}, to the system. This is expressed by

$$\mathrm{COP} = Q_{useful\_load}/E_{ne} \tag{1}$$

For a heat pump system E_{ne} would be identical to the work input as electricity. Care needs to be taken here to define where Q_{useful_load} is measured. For laboratory measurements (including our own in this paper) it is measured at the outlet of the hot water cylinder. Thus, losses in the pipe work will reduce the overall COP of the hot water system in a real house.

A COP of greater than one will result if more energy is extracted from the system than the boost energy input, as should be the case with most solar and heat pump water heaters. By the way of comparison, a typical New Zealand standard domestic hot water cylinder (electric resistance heating) would have a COP equivalent of 0.67 (BRANZ, 2004), which means that the standing losses for electric systems are around 33%. This value is a national average measured from around 400 separate systems as part of the BRANZ Housing Energy Efficiency Project (HEEP). The standing losses were measured by monitoring the electricity use in households when there was no draw off of hot water compared to the total energy used for hot water heating.

When there is no environmental energy input, the COP is the same as the efficiency of the system. For a solar system with no boost the COP will be infinite as the denominator is zero. Thus, for solar systems the solar fraction (SF) is the more usual defining term and is defined as the proportion of the total load that has been met using solar gain (expressed as a percentage). The solar fraction is given by Eq. (2), and represents the percent savings achieved compared to a reference (usually electric) domestic water heater (Duffie and Beckman, 1991). For the same useful energy delivery (Q_{useful_load}) from both the solar and the reference systems

$$\mathrm{SF}(\%) = 100 \times (Q_{ref} - E_{ne})/Q_{ref} \tag{2}$$

and as

$$Q_{ref} = Q_{useful\_load}/\mathrm{COP}_{ref} \tag{3}$$

$$\mathrm{SF}(\%) = 100 \times (Q_{useful\_load} - E_{ne} \times \mathrm{COP}_{ref})/Q_{useful\_load} \tag{4}$$

or

$$\mathrm{SF}(\%) = 100 \times (1 - \mathrm{COP}_{ref}/\mathrm{COP})$$

The solar fraction is identical to the percentage savings and as a fraction is given the symbol f_R (Morrison and Tran, 1984) and f_i (for the ith month) (Duffie and Beckman, 1991).

$$f_R = 1 - \mathrm{COP}_{ref}/\mathrm{COP} \tag{5}$$

The difficulty of using solar fraction, or percentage savings, as preferred descriptors for solar systems is that these quantities depend on the efficiency of a nominated reference system (this efficiency will be the same as COP_{ref}), and thus the descriptor will be dependant on environmental conditions including the ambient dry bulb temperature. In Europe, the reference system is likely to be a fossil-fuel-powered boiler system rather than a resistively heated electric system, further complicating the situation (Thur et al., 2006).

Another descriptor is the ‘‘solar contribution to the useful load’’ f, which is defined as (e.g. Morrison and Tran, 1984)

$$f = (Q_{useful\_load} - E_{ne})/Q_{useful\_load} \tag{6}$$

or

$$f = (\mathrm{COP} - 1)/\mathrm{COP} \tag{7}$$

And thus if the solar contribution to the useful load (f) and the solar fraction, SF (or f_R) are known then the COP_{ref} can be calculated from

$$\mathrm{CO}_{ref} = (1 - f_R)/(1 - f) \tag{8}$$

Andersen (1998), working at the Technical University of Denmark, defined the ‘solar fraction’ as the net utilised solar energy (NUSE) divided by the energy drawn off from the system Q_{useful_load}, where NUSE $= Q_{useful\_load} - E_{ne}$. This quantity is the same as the ‘solar contribution to useful load’ but different to the Duffie and Beckman (1991) definition of solar fraction.

Carrington et al. (1984) used another term the ‘System Performance Factor’ or SPF to categorise heat pump systems. The SPF was defined as the ratio of the equivalent electrical energy input into a resistively heated system to the actual energy used by the heat pump. In our notation this factor would be given by

$$\mathrm{SPF} = Q_{ref}/E_{ne} \tag{9}$$

And thus for the test system

$$\mathrm{COP} = \mathrm{SPF} \times \mathrm{CO}_{ref} \tag{10}$$

The above representation for SPF, however, as used in this paper is not universal as in some instances SPF is used to denote the COP of the whole system rather than a component such as a heat pump unit (no storage).

In addition to using COP to characterize short-term laboratory-based measurements of heat pumps, the long-term performances of solar or heat pump systems that are permanently connected to a (main or backup) energy supply can be represented by a COP. Here the COP is calculated over the period of concern i.e. day, month or year. It is important to note that COPs cannot be averaged, but the aggregate COP can be calculated for the period of concern by dividing the total energy output over the period divided by the total non-environmental energy input over the period. In the later discussion, descriptors used in other internationally published results for solar systems and heat pumps are converted to COPs and compared to our own results using the relationships as given above.

While E_{ne} is well defined and can be measured directly for an electrically boosted system by integrating the electrical power over the time period, Q_{useful_load} is more difficult to measure as it needs to be ascertained by knowing the flow rate of the output water and the temperature difference between the hot water output and the cold water input. As the temperature in the storage cylinder of a solar system is frequently above the thermostat set point due to solar gain during the day, a set volume of water can have a varying Q_{useful_load} on any given day depending on the cold water temperature (T_{cold}) and the actual temperature reached by the system during the day (T_{hot}).

$$Q_{useful\_load} = mC_p(T_{hot} - T_{cold}) \tag{11}$$

where m is the total mass of water output over the time period and C_p is the specific heat of water at the mean water temperature.

The energy payback time can then be calculated as a function of COP and useful load. The loads used for comparison are those defined in AS 4234 (1994) that is 25.6, 39 and 52 MJ/day. These values correspond to between 135 l/day and 275 l of hot water per day, the values are variable because of variable cold water input temperatures. The energy saving from the solar systems using electrical boost or a heat pump system must first be converted into primary energy using the appropriate factor for the country. For grid systems using mainly fossil fuel inputs a suitable factor is 3.4 (Crawford and Treloar, 2004) for New Zealand, which uses mostly renewable energy a ratio of 1.5 can be calculated for 2006 (EDF, 2007).

The conclusion from the above analysis is that COP is a useful quantifier for both heat pump and solar systems and as such it may have advantages in quantifying system performance in terms of policy formulation.

3. Comparison of systems

Our experimental results have been reported separately (Kerr and Lloyd, 2006). With an annual average solar insolation of 11 MJ/m^2/day or 3 kWh/m^2/day, Dunedin has the lowest solar radiation of any of the main centres in New Zealand. Nevertheless, the solar regime is comparable with many parts of Germany and better than most of the UK. The performances of two of the flat plate systems we tested, with COPs of 0.64 and 1.02, were not, however, considered satisfactory. The pumped system with the COP of 0.64, in particular, had a COP slightly poorer than the reference resistively heated electric storage system and the thermo-siphon system tested could almost be equalled by a either an instantaneous resistively heated electric system (or gas) or a super insulated resistively heated storage system. It might be noted here that the performance for the particular systems is not suggested to be relevant to generic systems of the type described and in fact discussions with the manufacturer’s representative have led us to believe that the flat plate thermo-siphon system, at least, was not installed optimally for the latitude of Dunedin and that there were a number of endemic problems with the pumped flat plate system, which if corrected would considerably enhance the performance of that system. In particular, this latter system was plumbed to a conventional hot water storage tank with an uncontrolled boost element and a heat transfer system that was non-standard. The aim of the present series of tests was, however, not to test optimum systems but to gain some idea of the performance of actual systems as they might be installed in the wider community. Clearly there is room for improvement in this regard. Results by Guthrie et al. (2005) suggested in their paper that the performance of systems in-situ may improve if a large subsided rollout is put in place with recognition given to improved performance. This finding is particularly relevant to the New Zealand situation as the current (2007) subsidy scheme is strongly performance based.

In terms of international comparisons, as mentioned, there is a relative dearth of reliable data for complete systems, especially in-situ testing. Carrington et al. (1984) measured laboratory performance of a specific design of hot water heat pump (separate condenser and evaporator with pumped flow to an existing storage tank) with COP results ranging from 2.39 to 2.95 for an output water temperature of 55 °C and ambient temperatures between 5 and 20 °C. The same group measured in-situ results for seven heat pump hot water heaters located in residential households in Dunedin and Auckland, finding ‘System Performance Factors’ ranging between 1.6 and 2.6. These SPF values would correspond to COPs ranging from 1.06 to 1.7 using a reference COP (COP_{ref}) of 0.67, suggesting that in-situ results for complete systems may be somewhat lower than laboratory measurements. The in-situ measurements were for heat pump systems retrofitted to existing storage tanks, which at that time were relatively poorly insulated. The tank standing losses reported by Carrington et al. (1984) were given as 2.63 kWh/day for a 180 l tank at 55 °C. The BRANZ (2004) standing losses for the 2004 HEEP study were comparable and were measured between 2.2 kWh/day for well-insulated 180 l storage tanks and 2.7 kWh/day for the same size less well-insulated tanks and measured at actual storage temperatures experienced in-situ.

Morrison et al. (2004) tested both solar systems and heat pumps. For heat pumps they found that in Sydney, Australia a COP of 2.3 was possible for a heat pump system in a laboratory situation with an integral condenser and 1.8 for systems with an external condenser. Lloyd (2001) found exactly the same value (2.3) for the COP of heat pump hot water systems (integral condenser) used in-situ in Aboriginal communities in central Australia. Our present results indicate COPs of just under 2 could be obtained in Auckland, which has a somewhat cooler climate than Sydney. Merrigan and Parker (1990) found in Florida, USA that, “Heat pump water heaters have a system efficiency roughly twice that of an electric resistance heater and operate at a load factor of 52%”. This would correspond to a COP of 1.64 given that in Florida the reference electric heaters had an average COP of 0.82.

For solar systems Prud’homme and Gillet (2001) found with advanced control technologies that COPs of between 1.5 and 1.7 were possible for flat late solar domestic systems in Switzerland. Knudsen (2002) at the Technical University of Denmark found that consumer behaviour had a great influence on performance and that: “A previous investigation showed that the thermal performances of small Danish SDHW systems are much lower than expected and that the thermal performances of systems in practice are lower than the thermal performances of similar systems tested in the laboratory”. Andersen (1998), working at the same institution in Denmark, measured the laboratory performance of 18 different systems (with collector areas from 4 to 6 m^2 and tank volumes ranging from 200 to 300 l) and in addition measured the in-situ performance of a further 32 systems. The results for both the laboratory tests and the in-situ testing were reported using annual NUSE and the annual solar fractions.

These results show a much higher variability for the in-situ measurements, as might be expected considering a much wider range of draw of volumes that occur in real household. When the reported solar fractions and ‘net utilised solar energy’ (NUSE) were converted to COPs they gave an aggregate COP for the 18 laboratory measurements of 1.9. The corresponding value for the in-situ results was found to be 1.7, suggesting that the in-situ results were around 12% lower than the laboratory results. Fig. 1 shows the spread of COPs from the Andersen data set. The annual average insolation for Copenhagen is close to the Dunedin value of 3 $kWh/m^2/day$ and the annual average temperature is also close to the Dunedin annual average of 11°.

Tully (1995), working in South Africa, found that the backup element size had a marked effect on the COPs of solar thermosiphon systems. This researcher found for a horizontal tank and a 1 kW element, a COP of 2.1. Using a vertical tank, which enables a higher degree of thermal stratification, the COP improved dramatically to 3.9 for a 1 kW element and 3.0 for a 6 kW element. Morrison and Tran (1984) measured COPs for thermo-siphon systems of around 2.3 and Lloyd (2001) found a COP of around 1.7 for thermo-siphon systems monitored in-situ, but this was for Aboriginal communities in central Australia where the daily draw off rates were extremely variable and often very high. Van Amerongen and Bergmeijer (1991) found energy savings between 23% and 51% for a series of domestic solar hot water systems in the Netherlands. These researches also suggested that their work showed “clearly that the actual energy savings of a SDHW heavily depend on the performance of the total combination of SDWS and auxiliary heater”.

Figs. 2–4 show results from the literature research converted to COP values of actual operational solar systems and heat pumps of various types plus our own results for Dunedin as a function of both average annual solar radiation ($kWh/m^2/annum$) and average annual ambient temperature. As can be seen, average ambient temperature with an R^2 value of 0.43 ($R = 0.65$) is a better predictor of system performance than solar radiation for solar systems (with $R = 0.65$ and 15 measurements there would be a 99% chance of a correlation existing between radiation and COP). Note that the trend lines are not to be interpreted as assuming a linear relationship between COPs and either ambient temperature or solar insolation but as a means of comparing solar system performance with heat pump system performance (Table 1).

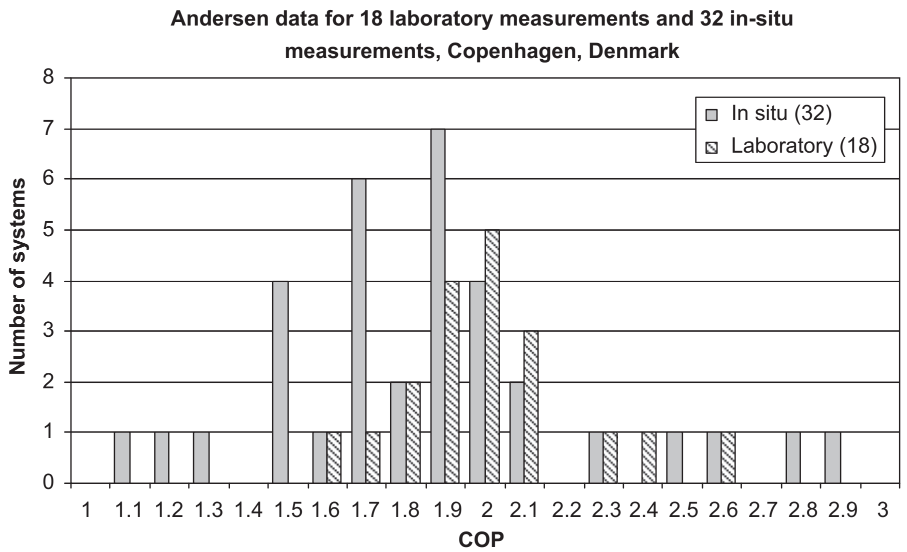

Fig. 1. Solar system performance data: from Andersen (1998).

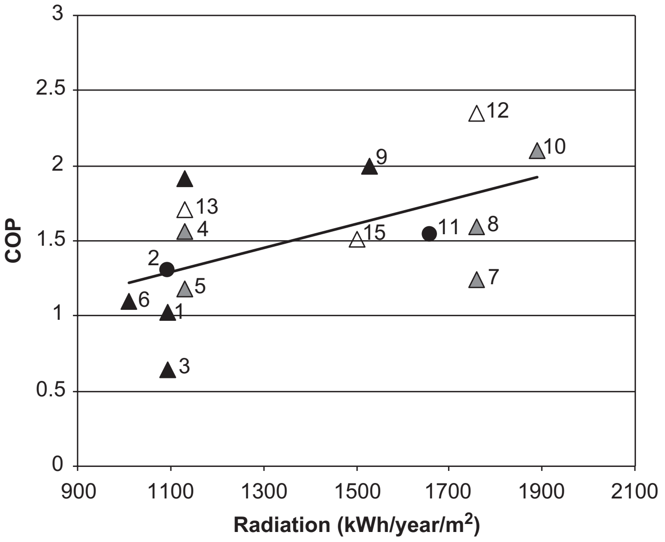

Fig. 2. COP versus solar insolation, solar systems.

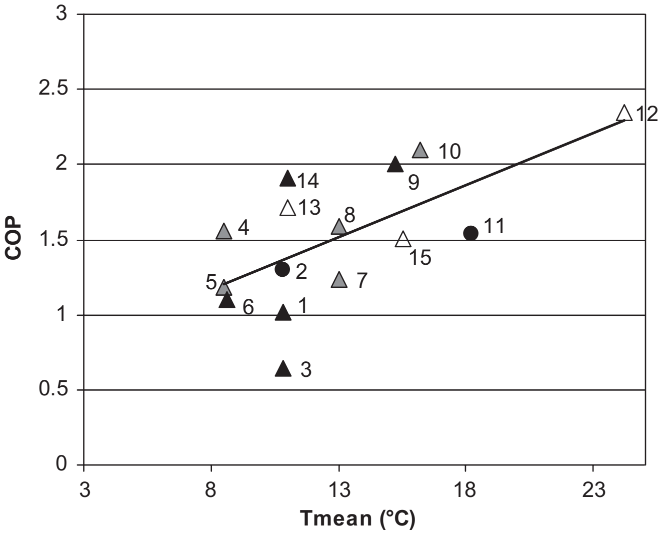

Fig. 3. COP versus ambient temperature, solar systems.

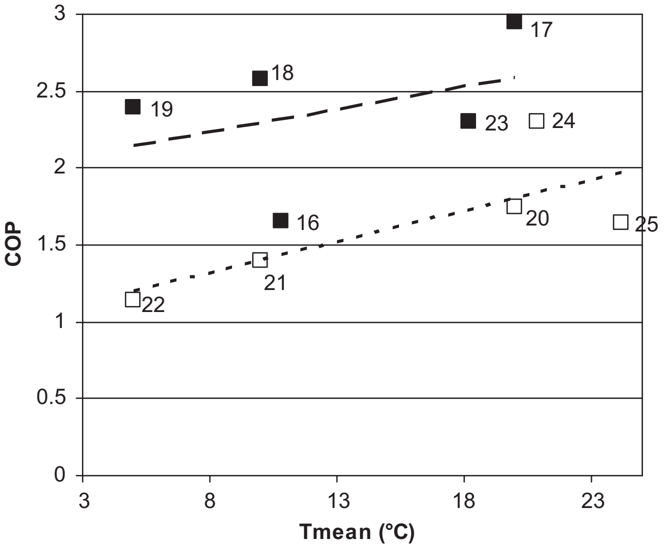

Fig. 4. COP versus ambient temperature, heat pump.

Source of climate data: RETScreen® International, Clean Energy Project Analysis Software, Version 3.1, Minister of Natural Resources Canada 1997–2005, CTEC-Varennes (RETScreen, 2005).

The conclusions that can be reached from the above experimental results suggest COP values for heat pump hot water systems and direct solar systems with a permanently connected boost showed considerable overlap for most temperature regimes and they thus should be considered equal in terms of policy decisions. Heat pump systems are less likely to experience poor performance due to variations in draw off times or a lack of control strategy, but solar systems on the other hand have the potential to produce hot water without any non-environmental energy. As per Andersen (1998) it might be expected that variations in draw off could cause a variation in performance of around 12%. The heat pump system tested had a thermostat set temperature of 55 °C, with typical outlet temperatures recorded in the range of 48–52 °C. These temperatures, however, do not meet the local building requirements for Legionella control in New Zealand, which requires that the temperature of the storage medium be 60° or above for at least 1 h week.

4. Embodied energy and energy payback time

The embodied energy of solar systems was taken from a paper by Crawford and Treloar (2004), who modified an earlier calculation by O'Sullivan and Meldrum (1982). The 2004 paper gave a value of 34.47 GJ (9.6 MWh) of primary energy for an electric-boosted thermo-siphon, flat plate solar system including installation. This value, which was calculated from the embodied energy of the system components, is very close to what would be expected based solely on the cost of the system. In New Zealand for instance the 2005 national energy use per dollar of GDP (the energy intensity) was 1.4 kWh/NZ$ (Lloyd, 2007). The indicative cost of a solar hot water system of roughly the same vintage (2006) was around NZ$7000, including installation, which would mean the energy attributable to this expenditure was 9.8 MWh. If this relation holds true for heat pump hot water systems it could be estimated that these systems might have an embodied energy of comparable to the solar systems given that the installed cost is somewhat similar. It might be noted, however, that it cannot always be assumed that the embodied energy can be worked out using this method but for the particular instance cited the embodied energy calculated from independent methods using real energy data does agree with that calculated from kWh/GDP. For comparison the annual average energy use per residential household per year in New Zealand in 2006 was 11.6 MWh. So the energy cost of such energy-efficient systems is a little less than the annual household energy consumption in New Zealand. As noted earlier, the payback time is also dependant on the conversion ratio for consumed energy (electricity) to primary energy and this ratio thus depends on the grid system. Two examples were used, namely Australia with mostly fossil fuel fired generation and New Zealand, which has mostly renewable generation (hydro and geothermal).

The results are given in Figs. 5 and 6 and as can be seen they confirm the conclusions of Crawford and Treloar that for electrical-boosted solar systems in Australia with COPs around 2 and a load of around 52 MJ/day that the energy payback time is indeed around 6 months. The conclusions reached here, however, suggest that for lower loads, poorer COPs and for less favourable solar regimes (in countries such as New Zealand) the energy payback times for solar hot water systems can extend to around 8 years. In terms of policy directions coupling hot water savings with high capital cost solar or heat pump systems does not make sense.

Table 1
Keys for Figs. 2–4

	Model only	Laboratory	In-situ
Flat plate	▲	▲	△
Evacuated tube		●	○
Heat pump		■	□

	Location	References	Notes
1–3	Dunedin (New Zealand)	Present results	Laboratory but based on whole systems
4, 5	Switzerland	Prud'homme and Gillet (2001)	Model based on whole systems
6	The Netherlands	Van Amerongen and Bergmeijer (1991)	Laboratory but based on whole system
7, 8	Canberra (Australia)	Dennis (2002)	Model based on whole system
9	Auckland (New Zealand)	Present results	Inferred result from laboratory in Dunedin
10	South Africa	Tully (1995)	Model based on whole system
11	Sydney (Australia)	Morrison and Tran (1984)	Laboratory but based on whole system
12	Florida	Merrigan and Parker (1990)	In-situ measurements in family residences
13, 14	Denmark	Andersen (1998)	Laboratory tests and in-situ measurements
15	Melbourne (Australia)	Guthrie et al. (2005)	In-situ measurements
16	Dunedin (New Zealand)	Present results	Laboratory based on whole system
17–19	New Zealand	Carrington et al. (1984)	Laboratory tests with no storage
21, 22	New Zealand	Carrington et al. (1984)	In-situ tests of complete systems
23	Sydney (Australia)	Morrison et al. (2004)	Laboratory but based on whole system
24	Alice Spring (Australia)	Lloyd (2001)	In-situ measurements in four remote aboriginal communities
25	Florida	Merrigan and Parker (1990)	In-situ measurements in family residences

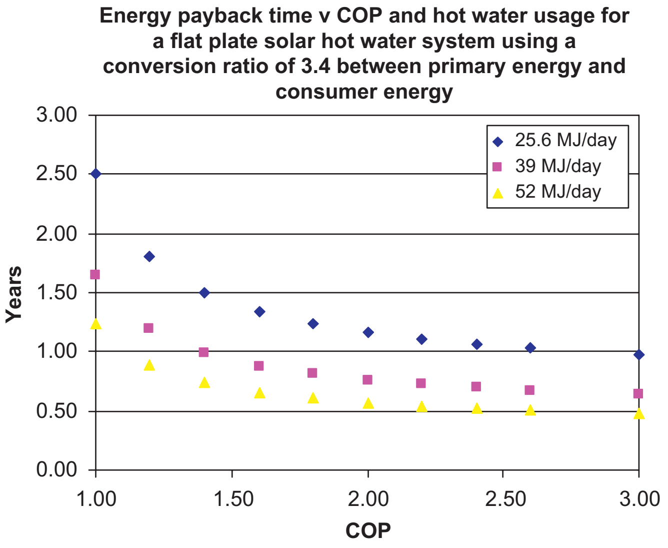

Fig. 5. Energy payback time versus COP and hot water usage for a flat plate solar hot water system using a conversion ratio of 3.4 between primary energy and consumer energy.

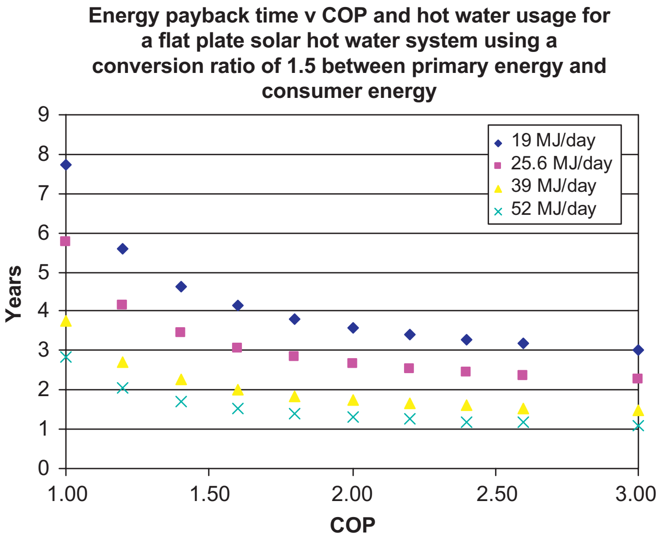

Fig. 6. Energy payback time versus COP and hot water usage for a flat plate solar hot water system using a conversion ratio of 1.5 between primary energy and consumer energy.

5. Conclusions

The main conclusion of this research is that reliable data are needed on the performance of solar and heat pump systems to allow informed policy decisions to be made, especially where government funds may be used to promote deployment of such systems. If solar and heat pump systems are considered as a means of reducing a country's greenhouse emissions and dependence on imported energy supplies there should be empirical evidence to show that this will in fact occur and that the move to such technologies will not just increase the embodied energy component. The results reported here suggest that solar hot water systems are marginal in the lower parts of the South Island in New Zealand in terms of performance, if the systems do not have some control of the boost element activation. By marginal it is meant that the systems may consume more boost energy over their lifetimes than they produce as hot water over the same time; a situation that would suggest that instantaneous heaters with no significant storage losses would be a preferable option. The results also suggest that heat pump systems compete over all temperature regimes with direct solar systems. This conclusion is in some disagreement with a simulation study undertaken by Aye et al. (2002) at Melbourne University, Australia where it was found that direct solar systems outperformed heat pump systems for the warmer cities in Australia but heat pump systems were better performers in the cooler environs of Melbourne and Hobart. It might be noted here that most population centres in New Zealand are cooler on average than Melbourne. The present results, however, did not have access to results for solar systems operating in very high sunshine conditions.

In terms of the product type tested, the evacuated tube product gave the best results for a direct solar system giving savings of 1.25 times that of the (selective surface collector) flat plate thermo-siphon system on a square metre of collector area basis. This result is consistent with other research; Morrison and Tran (1984) for instance found that the efficiency of evacuated tube collectors was about 1.8 times that of a non-selective surface flat plate collector and 1.3 times that of a selective surface flat plate collector per collector area when measured in Sydney, Australia.

There was, however, a substantial spread in performance between the products as tested as found by Andersen (1998). In New Zealand, heat pump technology is likely to result in a better match between security of supply, GHG emissions and reduced peak transmission loading compared to the solar option and therefore should be considered as a part of a strategy to reduce household energy consumption.

The research also found that the performance of both types of technologies, particularly solar systems, can be markedly improved through the use of auxiliary controllers (e.g. timers) to prevent the non-environmental energy source coming on during the daytime. This result is in good agreement with Prud'homme and Gillet (1998), who found that the solar fraction increased from 15% to 46% with the introduction of an optimal boost control strategy. Heat pump systems are likely to benefit from the use of timer set for afternoon operation during the winter months to reduce the risk of icing of the evaporator coils. Further work needs to be done on optimising the boost control methodology as applying it to real households will have to take into account the complexities of highly variable draw off rates and times and possible interaction with utility load control strategies.

New Zealand is currently adopting a common set of standards with Australia in order to encourage the industry to maintain a higher level of product but this is difficult to enforce especially when systems are allowed to be retrofitted to existing storage tanks, as was the case for the pumped flat plate collector tested. In addition, unless the standard requires physical testing of all combinations of product available, a move that would be both expensive, time consuming and resisted by the industry, real savings from systems with a high degree of user variability are unlikely to match those promoted by the industry and, importantly, used to calculate greenhouse gas savings. In this regard the move by the New Zealand government to implement a subsidy program based on whole system performance, as determined by TRNSYS simulations, (with physical measurements for components) is clearly in the right direction.

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