SIDE BY SIDE TESTING OF EIGHT SOLAR WATER HEATING SYSTEMS

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EXECUTIVE SUMMARY

The principal goal of the project described in this report was to compare the amount of energy which eight modern solar water heating systems could produce over an average year. The method employed for the work was largely specified in a Feasibility Study carried out prior to this project by a third party for the DTI.

Previous projects which have set out to collect data on the performance of active solar water heating systems have often monitored installations in real buildings, with real loads imposed by the occupants. Whilst many of these projects have produced measurements of the performance of particular systems under particular load and climate conditions they have failed to produce information which can readily be extended to other applications. They have also not generally produced results which allow direct comparison between systems: it is unusual for multiple systems to be installed at the same site and subjected to the same load pattern.

Climatic conditions are one of the key factors determining system performance, and this in turn implies that it is desirable that tests on alternative systems should be carried out under the same climate. The Feasibility Study concluded that the most appropriate way of conducting the tests was in a side by side configuration. The requirements for multiple systems and for standardised load patterns suggests that the tests are most appropriately carried out at a laboratory facility.

Previous laboratory work on active solar water heating has often concentrated on the issue of collector performance. This project adopts a different approach by setting out to measure the performance of eight complete systems, each one comprising collector, storage tank and a means of moving fluid, and hence energy, between these components.

To achieve this goal the Energy Monitoring Company Ltd has constructed a purpose built facility at their outdoor test site at Cranfield in Bedfordshire. The facility houses eight complete solar water heating systems, and allows all to be subjected to identical hot water demand profiles. Data has been collected from the facility over the period from January to July 2001, providing a good mix of winter and summertime weather. Since the eight systems operate side by side they are all exposed to the same climate.

The performance of each system has been monitored in detail, using measuring equipment which can be traced back to national standards. The climate to which the systems were exposed has been measured, and the volume of hot water delivered by each system each day recorded. The hot water delivery temperature, cold water supply temperature and temperature of the enclosure which houses the system storage tank have all been monitored.

Finally, the amount of parasitic electrical energy that each system consumes to produce that hot water has been metered and recorded. This latter information allows a more comprehensive estimate of the net environmental benefit of each system to be made.

The recorded data have been used to calculate the energy output of each system for each day. From this a functional relationship between solar radiation level and hot water delivery has been developed for each system. A second relationship has been produced to summarise the amount of electrical energy used. These relationships have been used to normalise the performance of each system to a full year of average UK climate. and determine the output and electrical energy consumption which would be expected.

A few minor problems occurred with some systems, but all were quickly rectified. Data from the periods when these problems occurred have been omitted from the analysis described here, and the performance figures presented therefore represent estimates of the benefits which would be obtained from systems which were working perfectly.

The principal conclusions of the work are that the facility which has been constructed is capable of providing consistent test results for all eight of the systems installed, and that each of the systems tested has proved capable of producing a useful amount of hot water under UK climate.

When the load consists of a single 150litre draw off early in the evening the extrapolated annual hot water production ranges from 3440 to 4820MJ. When the load is spread over the course of each day, with hot water draw offs in the morning, at lunch time and in the evening the corresponding range is 3620 to 4860MJ.

In assessing the value of the energy provided by each system it has proved vitally important to take into account the parasitic energy used to power controllers and pumps. The extrapolated annual parasitic energy consumption ranges from zero to 390MJ. Including this in the appraisal of the systems significantly changes the ranking of their performance, with one system moving from eighth to third place.

Most surprising is the relatively small sensitivity to the pattern of water draw off over the course of the day. Conflicting factors which affect the outputs of the systems have been identified: a draw off pattern which requires water early in the morning requires that some hot water is stored overnight, with corresponding losses, but at the same time it gives lower tank temperatures during the day, allowing the collectors to operate more effectively. In all cases these two effects almost exactly cancel out, leading to slightly higher outputs for some systems and slightly lower for others when changing from a single evening draw off to one distributed throughout the day.

As expected expressing these results in terms of collector efficiency reveals that the two evacuated tube designs operate at a higher efficiency than their flat plate counterparts. However they do not provide significantly more or less energy over the course of the year, and fall in the middle of the overall range of system outputs. This implies that the relative sizes of the systems almost exactly compensate for differences in system performance.

A series of recommendations has emerged from the project, and these fall into three categories: system installation, monitoring and further work which could now be carried out using the existing facility.

The presence of flow indicator tubes on some of the installations allowed rapid checks that working fluid was moving through the collectors to be made. This allowed a problem with a blocked valve on one system to be immediately diagnosed and repaired. However, a failed pump on another system which was not fitted with a flow tube was not diagnosed until the measured performance data was analysed. The installation of flow tubes on those systems which do not already have them would clearly be a valuable addition.

The redundancy built into the monitoring scheme has allowed minor problems to be rapidly diagnosed and rectified. More importantly it lends weight and credibility to the conclusions of the project as a whole. Future monitoring projects should consider carefully how to incorporate as much redundancy as possible. The relative benefit associated with each system is radically changed when the amount of electrical energy they use is considered. It is therefore vital that this is measured in future monitoring projects.

Further work has been identified which could explore the impact of other hot water run off patterns on the performance of the systems, and which could explore the impact of integrating auxiliary water heating with the solar systems. Finally, if part of the test facility was modified to allow a limited number of further trials to be carried out in accordance with international standards this would provide further confidence in the results derived from this project, and place them in the context of other results from around the world.

The goal of this project was to compare the energy performance of eight modern solar water heating systems. In assessing the mass of results presented it is important to remember that the amount of energy delivered is not the only criterion to be considered when selecting a system. Long term reliability, possible degradation of performance over the lifetime of a system and resistance to vandalism or accidental breakage may all be important in a given application. The assessment of these aspects of performance was outside the scope of this project, but their consideration may be vital for specific installations.

CONTENTS

1 INTRODUCTION

The principal goal of the project described in this report was to compare the amount of energy which eight modern solar water heating systems could produce over an average year.

Previous projects which have set out to collect data on the performance of active solar water heating systems have often collected data from installations on real buildings, with real loads imposed by the occupants. Whilst many of these projects have produced measurements of the performance of particular systems under particular load and climate conditions they have failed to produce information which can readily be extended to other applications. They have also not generally produced results which allow for direct comparisons between systems: it is unusual for multiple systems to be installed at the same site and subjected to the same load pattern.

Previous laboratory work on active solar water heating has often concentrated on the issue of collector performance. This project adopts a different approach by setting out to measure the performance of complete systems, each one comprising collector, storage tank and a means of moving fluid, and hence energy, between these components.

This report describes side by side tests carried out on eight solar water heating systems over the period from January to July 2001. The tests were carried out by the Energy Monitoring Company Ltd on a specially constructed facility at their outdoor test site at Cranfield in Bedfordshire. The approach adopted for the work followed closely the recommendations of a feasibility study previously carried out for the DTI by ESD [1].

Section 2 of this report describes the experimental approach adopted. Section 3 contains details of the systems which were installed for testing. In Sections 4 and 5 the experimental facility and its instrumentation are described in detail. Section 6 describes how the data analysis was carried out, with data from one system used to demonstrate the method used. In Section 7 results for all eight systems are presented, including a brief description of the technical problems encountered at installation time and over the course of the first six months installation. Finally, Section 8 summarises the conclusions of the project, and Section 9 details the recommendations which have emerged.

2 EXPERIMENTAL APPROACH

The Feasibility Study for this work [1] explored four potential testing strategies which could be adopted to provide the information required. These were:

- an Input/Output test procedure (as described in ISO 9459-2 [2]),
- a Dynamic System Test procedure (as described in ISO 9459-5 [3]),
- a Simplified Dynamic System Test procedure (developed at Cardiff University), and
- a Side by Side Test procedure.

The study examined the advantages and disadvantages of each approach and concluded that the Side by Side Test procedure should be adopted. In this procedure all of the systems to be tested are installed side by side on a test rig, and they are therefore exposed to identical climate. A fixed quantity of water is drawn off from each system at a specified time of day, and measurement of cold water inlet and hot water delivery temperatures allows the energy provided by each system to be calculated. This is carried out on a minimum of 50 days spread over the period from March to October. From the resulting data a relationship between energy delivered and incident solar radiation is derived, and this is used to predict the output of each system over a year of average climate.

No auxiliary heating is used in the Side by Side Test procedure, and it therefore determines the output of the solar heating system alone. This is equivalent to assuming that the solar cylinder is used as a preheat tank to a second cylinder, that auxiliary heating is provided by an instantaneous source, or that the householder switches off auxiliary heating and relies solely on solar heated water. The latter is unlikely to be the case throughout the year. In the situation where only one storage tank is installed and auxiliary energy is added directly to that tank it is likely that due to disruption of stratification and higher temperatures the collectors will run at a slightly reduced efficiency. The chosen test method does not address this issue.

In the early stages of the work described in this report a number of refinements and extensions to the test procedure proposed in the Feasibility Study were proposed.

The first of these related to the measurement of the 'parasitic' energy used by the pumps and controls of the systems. Although this will generally be a relatively small energy input it is likely to be in the form of peak rate electricity. Its cost is therefore relatively high, and its environmental impact significant. Furthermore, the amount of parasitic energy used varies between systems. In particular, one of the systems tested uses a small photovoltaic array to power its pump, and therefore consumes no energy at all from external sources. In order to make a fair comparison between the systems it was therefore considered vital that the electricity consumption of each system was metered. The way in which this was done is described in Section 5.2.

The Feasibility Study proposed that water be run off from each system into a metering tank. When the required volume had been delivered a float switch would be operated which would terminate the run off. The energy delivered would then be calculated by multiplying the average difference between inlet and delivery temperatures by the total run off volume and the appropriate heat capacity. This approach gives the correct result only if either the temperature difference or the flow rate is constant throughout the run off. It is likely that the storage tank will stratify to some degree, and in this situation the temperature difference will not be constant. The Feasibility Study did not call for the use of a flow controller, and any variation in the head of the water supply being used for the run off will thus cause the resulting flow rate to vary. In this situation using the mean temperature difference and total flow to calculate the energy delivered will introduce errors, which may be significant. To avoid this problem the flow was metered at five second intervals throughout the run off sequence. The use of metering tanks to control the run off was retained, and thus as well as allowing the delivered energy to be accurately calculated the flow meters provided a valuable double check that the system was operating as intended. The flow meters are described in more detail in Section 5.4, and the calculation of the delivered energy in Section 6.1.

The Feasibility Study proposed the use of a single run off sequence, in which 150litres of water was taken at 6:00pm each day. One of the weaknesses of the proposed testing method, acknowledged in the Feasibility Study, is that it provides no indication of how alternative run off sequences will affect system performance. To address this issue it was decided to carry out a second series of tests, in which water run off was distributed more evenly throughout the day. Table 2.1 describes the two run off sequences used. The run off schedules were timed using GMT throughout the test period.

Sequence	Time of day (GMT)	Volume run off (litres)
Single evening run off	6:00pm	150
Split run off	7:00am	60
	12:00noon	30
	5:00pm	60

Table 2.1: Run off sequences

In order to implement the split run off sequence two additional level switches were added to the metering tanks, allowing water to be run off in units of 30, 60 or 150litres. Since data from both sequences were required over the whole test period the two run off schedules were interleaved, with typically two to three weeks of one sequence before changing to the other for a further two to three weeks. The actual point at which the change over was made was determined after inspecting the weather data obtained over each period.

Although the Feasibility Study specified the volume of water to be run off each day it did not specify a flow rate. The rate at which water is removed from the solar tank can have a profound effect on the conditions within the tank, and it was therefore important that a realistic value was chosen, and that it was consistent between systems. The British Standard for domestic hot water installations [4] lists design flow rates which range from 3litres/minute for a handbasin, through 12litres/minute for a shower or kitchen tap up to 18litres/minute for a bath. The value of 10litres/minute recommended in [2] is in line with these figures, and was adopted for these trials. The rate at which water was run off from each system was manually trimmed to this value using a gate valve in each system.

The Feasibility Study had proposed that the tests be conducted from March to October. This has the advantage that the weather is likely to be bright and therefore performance parameters such as system efficiency can be measured with a high degree of certainty. However it has the disadvantage that by including only summer months it provides no information on the performance of the systems at low sun angles, or in prolonged periods of dull weather. To obtain this information it was proposed that the tests should instead be run from December through to June, thus capturing the full range of solar geometry. In fact minor delays meant that the tests actually ran from mid-January through to mid-July, still giving a good mix of winter and summertime conditions.

Finally, the Feasibility Study specified that data should be collected for approximately seven days each month, to provide the 50 points considered necessary for the proposed data analysis. Given the effort involved in constructing and instrumenting the test rig the additional effort associated with continuous data collection is relatively small. The advantages, however, are considerable:

- the increased number of data points means that the performance of the systems, and hence their likely annual outputs, can be derived with greater accuracy,

- data will be gathered over a wider range of climatic conditions, and

- because systems are generally operated continuously in real applications the test is likely to be seen as more realistic and its results considered more representative of actual system performance.

In response to these arguments data were collected continuously throughout the trial. When run off schedules were changed transient effects meant that data from the day of the change and generally also the following day could not be used. There were also a number of malfunctions of the systems, described in more detail in Section 7. As a result, approximately 160 days data was actually used in the final analysis.

3 DESCRIPTION OF SYSTEMS TESTED

The project Feasibility Study [1] recommended eight systems for test. Table 3.1 lists the systems. The manufacturers of these systems had each been given the chance to comment on the proposed test method, and had all agreed to participate in the trial.

AES ZEN
Fieldway
Filsol
Thermomax
Riomay
Spectrum Energy
Sundwell
Energy Engineering

Table 3.1: Systems proposed for testing

At the beginning of the project Sundwell decided that they would rather not participate, and withdrew. It was decided that AES should be allowed to install the system which they manufacture, as well as the ZEN system, which is imported. From now on the former system will be referred to as the AES system, the latter as the ZEN.

Later in the project Spectrum Energy also withdrew, and Solar Twin agreed to install one of their systems. Table 3.2 shows the final selection of systems tested, now listed in the order in which they were laid out on the test rig. The table also includes a brief description of the key features of each system.

1	AES	Selectively coated high absorbance and low emissivity flat plate system with one inner glazing layer of Teflon film and an outer one of Tedlar. Conventional controls and circulation pump.
2	ZEN	Selectively coated flat plate collector with low iron toughened glass cover. Drainback facility when system is not in use removes the need for antifreeze. Stainless steel mains pressure unvented cylinder, pump and sophisticated self-diagnostic controls are integrated in a custom wall mounting unit.
3	Solar Twin	Flat plate collector with absorber plate partially coated with low emissivity film glazed with twin walled polycarbonate. System is freeze tolerant, and circulates water directly from the base of the storage cylinder using a miniature variable low speed pump operated by a photovoltaic array.
4	Riomay	Evacuated tube system using six tubes mounted with their axes horizontal and absorber plates oriented towards the sun. Sophisticated electronic controls and conventional circulation pump.
5	Filsol	Flat plate collector with low emissivity absorber glazed with single layer plastic moulding. Conventional controls and circulation pump.
6	Energy Engineering	Vandal resistant flat plate collector glazed with twin wall polycarbonate. Conventional controls and circulation pump.
7	Fieldway	Flat plate system glazed with a single layer of Teflon film. Conventional controls and circulation pump.
8	Thermomax	Evacuated tube system using 20 tubes mounted with their axes running up the plane of the roof and connected to a manifold at the top. Conventional controls and circulation pump.

Table 3.2: Systems finally installed for testing

4 THE TEST FACILITY AND TEST REGIME

4.1 Collector mounting frame

In the majority of installations the collectors will be mounted on a roof. A tilt of 30° is typical of modern roofs, and the collector mounting frame was therefore inclined at this angle. All of the analysis of the data collected is related to solar radiation measured in the plane of the collectors, and thus any sensitivity to the angle of tilt is limited to geometrical effects.

In line with current standards for collector testing the frame was of open construction. This has the advantage that uniform temperature conditions are maintained all around the installation, and that they are the same for all the systems installed. However it does place systems which would normally be integrated into a roof construction, and would therefore have a warm roof space behind them, at a slight disadvantage.

Before the test frame could be designed in detail it was necessary to finalise the layout of the eight collectors, in order to determine the size of the frame. The principal criterion was that there should be sufficient gaps between the collectors to accommodate connecting pipework, and also to allow access to every collector without risk of damaging its neighbours. Figure 4.1 shows the layout which was finally adopted.

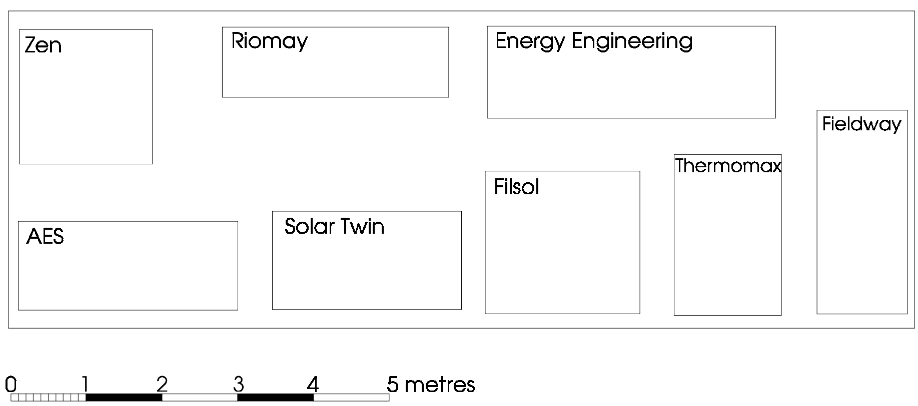


Figure 4.1: Layout of collectors on the test frame

With the layout of the collectors finalised it was possible to determine the size of the test frame. As the figure shows, the collector mounting area was approximately 4 × 12m.

The test site is completely unobstructed to the South. However, because the collector mounting plane is inclined there is the possibility of parts of it being overshadowed by obstructions to the North. Direct radiation could be obstructed at times of year when the path of the sun goes North of due East or West, and diffuse radiation could be obstructed at any time of year. Such overshadowing would affect systems at different positions on the test rig differently, and would therefore place some systems at a disadvantage.

Accordingly, the site and surrounding obstructions were surveyed, and the thermal simulation model TAS was used to predict the radiation level on each of the systems throughout the year. TAS was chosen for this task because, as well as carrying out a comprehensive geometrical calculation of the shading of direct radiation, it also calculates diffuse shading. The original intention had been to position the rig a distance of 6m from an adjacent test building, facing due South. When this configuration was simulated it was discovered that during July collectors at the western end of the rig received 1.5% less radiation than those at the eastern end. In response to this the separation from the nearby building was increased to 12m, and the rig oriented 5° East of South. Simulation of this revised layout indicated that the radiation falling on the most heavily shaded system was only 0.3% less than that falling on the least shaded collector. This was considered acceptable.

It was clear from the chosen layout that, due to their location on the facility, some collectors would potentially have shorter pipe runs than others, and would therefore be operating at a slight advantage. Once finalised the layout was used in conjunction with connection details of all the collectors to determine what the longest pipe run required would be. Other installers were instructed to route their pipes in such a way that they ran for the same distance before entering the shed housing the solar cylinder. In this way the losses from each system were equalised, ensuring that the test was carried out in a way fair to all systems.

4.2 Equipment enclosures

Four sheds were used to house the equipment associated with the eight installed systems, and also to house the instrumentation and data acquisition systems required to measure their performance. Before use the walls of the sheds were lined with glass fibre insulation and an MDF inner cladding. The floor and ceiling were insulated with polystyrene.

A room thermostat was installed in each shed, and in conjunction with a 500W wall mounted heater was used to maintain the temperature at a fixed value. This in turn ensured that the losses from each system were to a common temperature.

Figure 4.2 shows the test facility on plan.

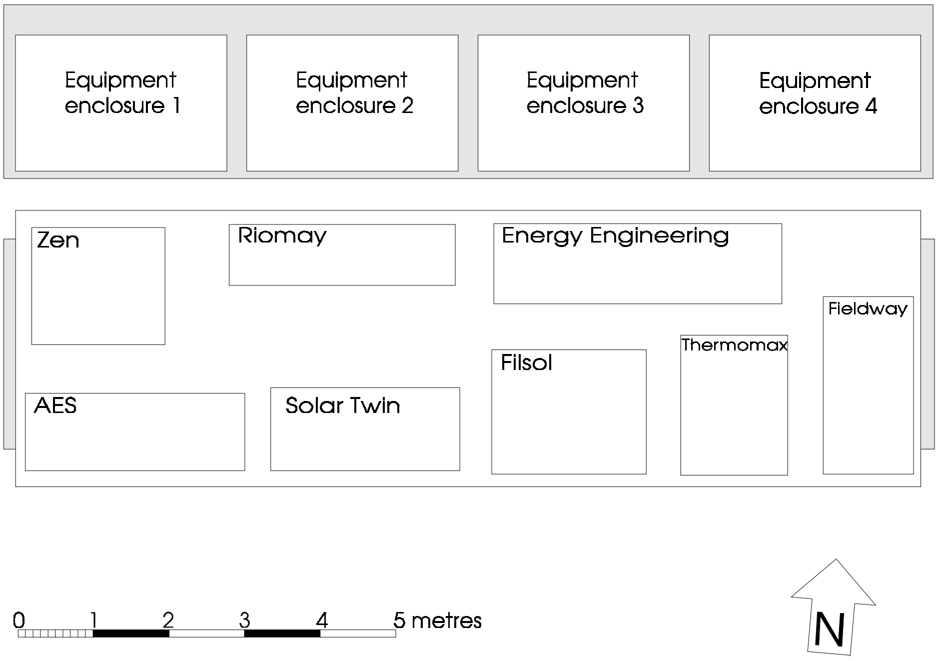


Figure 4.2: Plan view of the test facility

Finally, Figure 4.3 shows an elevation of the facility, viewed from the eastern end.

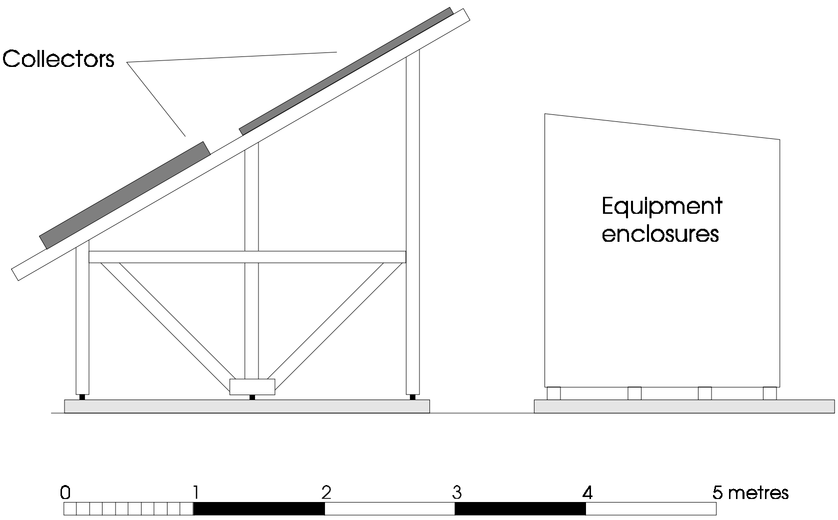


Figure 4.3: Elevation of the test facility

4.3 Water supply and metering

Figure 4.4 shows the layout of the plumbing associated with each of the systems. There was one cold water storage tank in each shed: thus each serves two systems. The positions of the flow meter and the inlet and delivery temperature probes are also shown on the diagram.

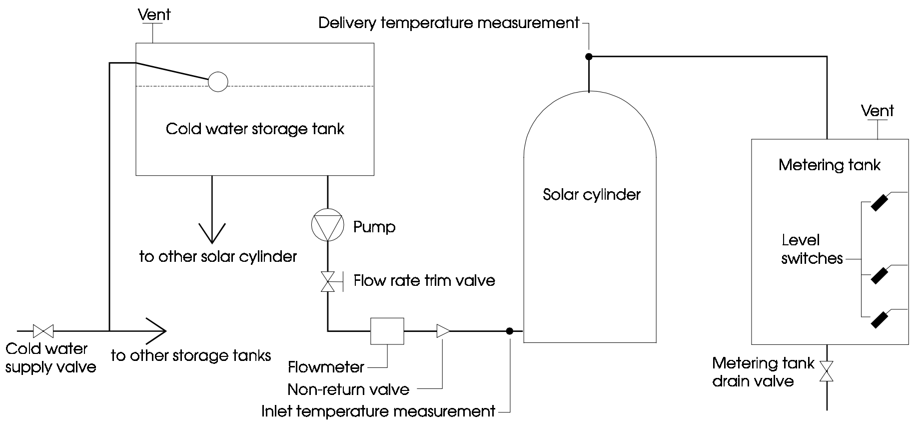


Figure 4.4: Layout of plumbing associated with each system

In operation, the cold water storage tanks are first filled by opening the cold water supply valve which controls the feed to all four tanks. This is done shortly before the first run off of the day, to avoid excessive preheating of the supply water and ensure that the inlet temperature to the solar tanks is as close as possible to the cold main temperature.

The drain valves at the bottom of each metering tank are normally held in the open position. This ensures that the tanks are empty at all times, even if a small amount of water has been pushed out of the outlet pipe by thermal expansion during the day. As well as guaranteeing that the tanks are empty prior to metering a run off, this minimises the risk of damage to the float switches should the metering tanks freeze.

When a run off is due, the valve at the bottom of the metering tank is first closed. The instruction to run off to the required level (30, 60 or 150litres) is then issued. This causes the pump to be energised, forcing water through the flow rate trim valve, the flowmeter and the non-return valve into the bottom of the solar storage tank. When the facility was constructed the level switches in each tank were positioned by filling the tank with a weighed quantity of water and setting the height of the switch so that it operated at the required point. When the selected level switch in the metering tank indicates that the required quantity of water has been run off the pump is stopped.

After a short wait the metering tank drain valves are again opened, and the water in each tank drained away.

4.4 Controls

The operations of filling the cold water storage tank in each shed, running water off to the level defined by a given level switch and draining down the metering tanks after the run off were controlled by a pair of time switches. Table 4.1 details the sequence of actions required to perform a single run off at 6:00 in the evening.

	Cold water supply valve	Run to 150 litres	Metering tank drain valves
Fill cold water tanks	15:45 ON		
	17:45 OFF		
Run off			17:45 OFF
		18:00 ON	
		18:30 OFF	
			18:45 ON

Table 4.1: Sequence of actions required for single evening run off

Table 4.2 shows the more complex sequence of operations required to implement the split run off schedule described in Section 2, in which 60litres is run off at 7:00am, 30 litres at 12:00noon and a further 60 litres at 5:00pm.

	Cold water supply valve	Run to 60 litres	Run to 30 litres	Metering tank drain valves
Fill cold water tanks	4:45 ON			
	6:45 OFF			
First run off				6:45 OFF
		7:00 ON		
		7:15 OFF		
				7:30 ON
Second run off				11:45 OFF
			12:00 ON	
			12:15 OFF	
				12:30 ON
Third run off				16:45 OFF
		17:00 ON		
		17:15 OFF		
				17:30 ON

Table 4.2: Sequence of actions required for split run off schedule

5 INSTRUMENTATION

In this section the instrumentation used to monitor the performance of the systems is described. The intervals at which measurements were made and the accuracies which can be expected of them are also specified.

5.1 Meteorological data

The key meteorological variable in this trial was clearly the amount of solar radiation incident on the collectors. This was measured using a Kipp and Zonen CM11 instrument, mounted in the plane of the collectors close to the geometric centre of the rig. This instrument has the advantage of built in temperature compensation and, more importantly, it is not prone to errors when operated on a tilted surface. This is clearly essential for the measurements made here. The overall accuracy of the instrument is ±2%.

External air temperature was measured behind the test rig frame. A PT1000 probe was used in a radiation shield. The sensor was mounted in a location between the collector mounting frame and equipment sheds where it was not exposed to direct solar radiation. The combined accuracy of the probe and shield in these circumstances is estimated to be ±0.3°C

5.2 System electricity consumption

The electrical energy consumption of each system was measured using a power meter supplied by Northern Design. This meter measures voltage and current consumption and integrates their product to provide a measure of total energy consumption. The meter also provides a measure of VA consumption, and hence of the power factor of the load. This facility was not used in this trial.

To provide adequate measurement resolution the meter was configured to provide 1 pulse per Watt hour of consumption. The meter has a basic accuracy of ±1%.

5.3 Supply and delivery water temperatures

The temperatures of water entering and leaving the solar cylinders were measured using PT1000 probes inserted into the flow. In order to minimise errors due to thermal conduction through the probe the cable was run back alongside the pipe and the whole installation insulated using 19mm pipe insulation.

The output of the sensors was recorded every 5 seconds whilst a run off was in progress. At other times the reading would not be reliable, as the stationary water around the probe would gradually warm or cool. No recordings were therefore made when a run off was not in progress.

The basic accuracy of the probes is specified as ±0.15°C at 0°C, rising to ±0.35°C at 100°C. Before use all of the probes were checked in a stirred water bath against a UKAS calibrated Quartz reference thermometer. In all cases it was found that the total system accuracy obtained from the probe and associated data logger was within the limits quoted for the probe alone.

5.4 Water volume

As described in Section 4.3 the volume of water run off from each system was controlled by monitoring the level in each metering tank. These tanks were calibrated by weighing the appropriate amount of water into them, and adjusting the heights of the level switches so that they operated at the appropriate point. In addition to this the flow rate was measured at 5 second intervals during run off using an electromagnetic flowmeter. This provided two useful features:

- by providing a continuous measurement of flow throughout the run off period the flow meter allowed an accurate determination of the actual energy delivered by each system. If the flow rate varied slightly over the course of a run off (due for example to changes in head) then the simpler approach of combining the total run off volume by the average temperature rise does not give the correct run off energy, and

- the total flow meter reading could be compared to the total run off volume expected. This provides a consistency check and, once consistency has been established, provides a way of detecting any problems with the run off system. In fact it indicated on a number of occasions that metering tank drain down valves were starting to leak due to contamination, and allowed the problem to be rectified (by dismantling and cleaning the valve) before the quality of data was compromised.

At the flow rate used for the run off sequences the meters have an accuracy of ±2%. The run off measured each day with each flow meter was typically within 1% of the nominal 150litres for which the metering tanks were calibrated.

5.5 Data acquisition system

Data was recorded using Etherlog data loggers manufactured by the Radio Data Logger Company Ltd. One logger was mounted in each of the four equipment enclosures.

Table 5.1 summarises the tasks carried out by the data loggers, and describes the three types of data record produced.

Task	Measurement Requirement(s)	Recording Requirement(s)
Shed data	Integrated electricity consumption of each system and shed temperature measured every 15 minutes	Record type 0 consisting of electricity consumption of both systems and shed temperature recorded every 15 minutes
Run off data (recorded only whilst running off)	System inlet and delivery temperatures and volume flow measured every 5 seconds	Record type 1 consisting of system identifier, inlet and delivery temperatures and flow recorded every 5 seconds for both systems
Meteorological data (recorded in Shed 3 only)	Solar radiation measured every 5 seconds and accumulated. Ambient temperature measured every 15 minutes	Record type 3 consisting of average solar radiation and ambient temperature recorded every 15 minutes

Table 5.1: Data acquisition tasks

As well as providing the flexibility to carry out these tasks in each shed the loggers were all equipped with a low power radio link. This allowed real time readings to be checked and recorded historical data to be transferred back to a central Personal Computer whenever required.

After transfer the files were run through a simple translation program. This fulfilled two vital functions:

- the data from each shed was split into two files, one for each system. This allowed manufacturers to be given access to their own data without them being able to see data from the system with which they shared a shed and data logger, and

- the meteorological data recorded on the logger in shed 3 was separated from the other data recorded in that shed and placed in a different file.

The format of the resulting data files is described in Appendix A of this report.

6 DATA ANALYSIS

In this section the processing of the data gathered over six months of testing is described.

6.1 Calculating system output

As described in Section 5 of this report the flow into each hot water storage tank and the corresponding inlet and outlet temperatures were measured every five seconds throughout each hot water run off. Given this information it is straightforward to evaluate the amount of energy delivered by each system.

To calculate the mass of water delivered it is necessary to know its density. Appendix B shows the density of water as a function of temperature, and shows that it varies by approximately 2% as the temperature changes from 10°C, a typical inlet temperature, to 55°C, the desired outlet temperature. This is a significant variation, and must be taken into account.

As Figure 4.4 shows, the volume of water run off is measured at the inlet to the hot water tank. Thus the mass of water which enters the tank is given by the measured volume multiplied by the density of water at the inlet temperature. However, we are interested in the quantity of water actually delivered. The volume of water expelled from the tank must be equal to the volume introduced, and therefore the mass of water delivered is given by the measured volume *multiplied by the density of water at the outlet temperature.*

At first this result seems counterintuitive: the mass of water leaving the tank should be equal to the mass of water entering it. In fact this is not the case. The tank is filled with the measured volume of water at the lower temperature, but during the day as it is heated it expands, and some water is forced out of the tank. On the test rig the water is forced out through the open outlet pipe into the metering tank from where it escapes down the drain. In a more realistic installation it would be forced up the vent pipe back into the cold water storage tank. In either case it is lost from the hot water system. It is this loss of mass which explains the apparent contradiction. The mass of water obtained from the system is therefore given by:

$$m = v \times \rho(T_{delivery})$$

where:

m is the mass of water run off in kg,

v is the metered volume in m^3, and

$\rho(T_{delivery})$ is the density of water at the delivery temperature in kgm^{-3}.

The energy required to produce this mass of water is obtained by integrating the specific heat capacity between the inlet and outlet temperatures. If the specific heat capacity was constant over this temperature range the correct answer would be obtained simply by multiplying the change in temperature by that constant. Appendix B also shows the specific heat capacity of water varies with temperature. The variation with temperature is seen to be smaller than for density, with the maximum variation of about 0.4% occurring between temperatures of 10°C and 30°C.

Given this relatively small variation, the required integral has been approximated by assuming the specific heat capacity to be constant at the value corresponding to the mean of the inlet and delivery temperatures. This would be exact if the variation of specific heat capacity with temperature was linear. As Figure B2 shows this is not the case. However, since the variation is small the error introduced by the approximation is also small. The energy output is therefore evaluated as:

$$Q_{out} = m \times (T_{delivery} - T_{inlet}) \times S((T_{delivery} + T_{inlet})/2)$$

where:

Q_{out} is the system output for the day in J,

$T_{delivery}$ is the hot water delivery temperature in °C,

T_{inlet} is the cold water inlet temperature in °C, and

$S((T_{delivery} + T_{inlet})/2)$ is the specific heat capacity at the mean temperature in $Jkg^{-1}K^{-1}$.

The above calculation assumes that all of the energy collected by the system is useful. The specification issued for all of the systems was a requirement of 150litres of water at 55°C each day. It could be argued that any water delivered above this temperature should not be counted as useful output from the system. However, in practice a householder would simply dilute such hot water with cold, to obtain the desired temperature. This would result in some hot water being left in the tank, where it could be used later. There would be some loss of this energy as it was stored overnight, but the majority would still be available the following day. In the analysis described here all the energy delivered by the systems has been assumed to be useful, even when its temperature exceeds the specified value of 55°C.

6.2 Relating system output to solar radiation

The amount of energy delivered by each system on a particular day is clearly strongly dependent on the amount of incident solar radiation. There are two reasons for wishing to develop a function which describes this dependence:

- it will allow the comparison of system performance to be made independently of incident radiation. Although the tests described here have been nominally carried out side by side there are some periods when individual systems were not running

- it will allow the performance of each system to be extrapolated to a whole year using long term average climate data

In any long term trial such as this it is inevitable that some of the data produced will not be suitable for analysis. For example, there will be days when the run off schedule is being changed over, there may be days when systems develop faults, and there may be days when the run off procedure does not go according to plan. To deal with all of these events daily data had to pass a range of tests before being included in the analysis described below:

- date selection: a list of dates from which data could be used was prepared for each of the two run off schedules. Days on which the run off schedule was being changed were excluded from the list. The dates of a short power cut and of the following day were also excluded. A complete list of the dates used to produce the data analysis described in this report has been supplied with the project data set and is described in Appendix A,

- flow selection: the total flow from each system was checked. If it was outside the range 135 to 165litres (±10% of the nominal value) then data from that day were discarded. This test removed data from the occasional days when contamination of a metering tank drain valve caused it to leak when shut, and resulted in excess flow as water leaked out of the metering tank during the run off. It also rejected data from two days when a small piece of grit partially blocked one of the cold water tank ball valves, causing the tank to only partly fill and resulting in a reduced run off volume for the two systems fed from that tank, and

- collector performance selection: if it could be confirmed that the output of a system indicated operation at an efficiency of less than approximately 40% of the nominal efficiency then data were rejected. This criterion served to remove data from days when systems had failed, either by boiling over or through controller or pump failure.

Figure 6.1 shows the data which remains for the AES system after the above criteria have been applied when the single evening run off schedule was in operation. The graph shows the daily system output as a function of solar radiation. There is a clear linear relationship, and the best fit straight line, obtained by regression, is also shown on the figure.

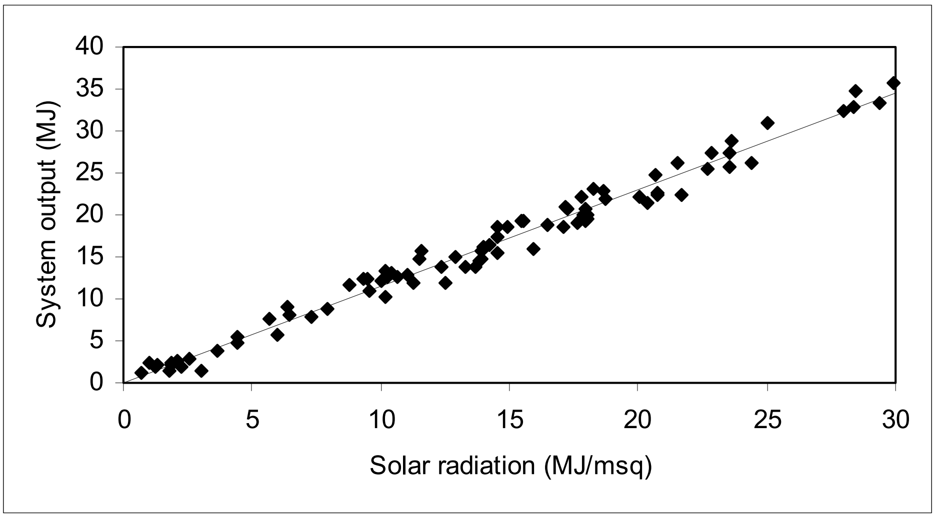


Figure 6.1: Daily system output of AES system as a function of solar radiation (single evening run off)

The parameters which define the straight line are readily obtained using linear regression, and are summarised in Table 6.1. In keeping with the notation adopted in the Feasibility Study the offset of the line is denoted by A0 and the slope by A1, that is the daily output of the system is given by:

$$Q_{out} = A0 + A1\ Q_{solar}$$

where:

Q_{solar} is the solar radiation incident on the system in Jm^{-2}, and

A0 and A1 are the model parameters.

Both of the model parameters have a physical interpretation. A1 has units m^2, and represents the effective collection area of the system, that is the area of ‘perfect’ solar collector with 100% efficiency and zero losses which would be required to replace the system. When related to the actual collector area it can be used to derive a system efficiency. We return to this in Section 6.5. A0, which has units J, represents the amount of energy produced by the system on a day when there is no solar radiation. This energy will principally come from conductive gains to the solar storage tank from its warm surroundings. For the well insulated tanks used in the systems described here these are likely to be small. Some of the control systems employed will run the pump periodically even on very dull days, just to check that no energy is available from the collector. In this case a proportion of the pumping energy will be transferred to the water. However, if external temperature is lower than the water supply temperature then a proportion of that energy will be lost by conduction from the outdoor parts of the system. Once again, the net energy transfer is likely to be small. We conclude that the value of A0 is likely to be very small, and Figure 6.1 confirms that this is indeed the case for the AES system.

Table 6.1 gives the values of A0 and A1 for the first system on the test rig, the AES system. As well as the best estimates of the model parameters the table gives their 95% confidence intervals.

A0	0.10 ± 0.57MJ
A1	$1.148 \pm 0.036m^2$

Table 6.1: Performance parameters for the AES system (single evening run off)

The table demonstrates that for this system the parameter A0 cannot be distinguished from zero. In this situation it is of interest to consider a simpler model in which we force its value to be exactly zero. In this case the equation summarising collector performance becomes simply:

$$Q_{out} = A1' \, Q_{solar}$$

where:

A1' is the single parameter of the simplified model.

Using this simplified model makes very little difference to the resulting predictions of system performance: it is not necessary to move the line shown on Figure 6.1 by very much to make it pass through the origin. However, the simplification does have a significant advantage. Since only one parameter is now being estimated from the data it can be derived with considerably more confidence. Table 6.2 shows the result.

A1'	$1.154 \pm 0.017m^2$

Table 6.2: Performance parameters for the AES system (single evening run off: simplified analysis model)

The parameter A1' has a useful interpretation in terms of system efficiency, and was therefore calculated for all combinations of system and run off pattern. The results are presented in Section 6.5.

When a split run off schedule is used the correlation between daily solar radiation and daily energy delivery breaks down. The next graph shows this effect for the AES system.

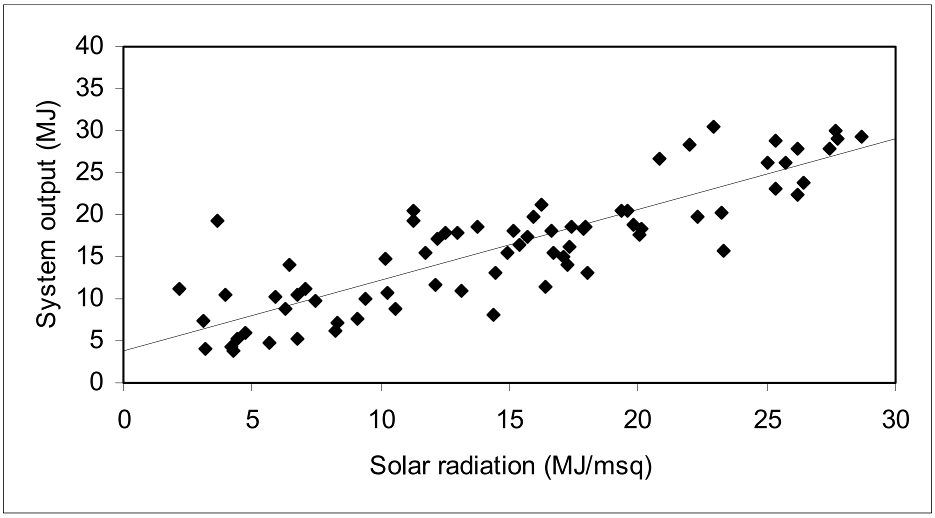


Figure 6.2: Daily output of AES system as a function of solar radiation (split run off)

The reason for this is simple: 40% of the water is run off from the system at 7:00 am, before any energy has been gathered from that day's solar radiation input. Thus the net system output for the day would be expected to be related to the previous afternoon's solar input as well as to the current day. The simple expedient of starting the 24 hour average of solar radiation at 12:00 noon on the previous day rather than at midnight results in a greatly improved correlation, as seen on the next graph.

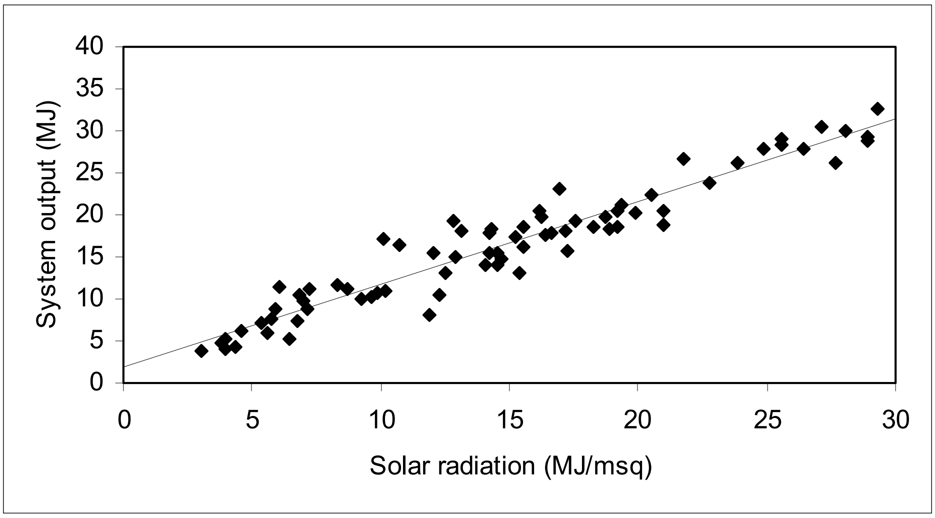


Figure 6.3: Daily output of AES system as a function of solar radiation (split run off and adjusted solar averaging)

Table 6.3 shows the resulting estimates of the coefficients A0 and A1.

A0	1.85 ± 1.14MJ
A1	0.985 ± 0.069m^2

Table 6.3: Performance parameters for the AES system (split run off)

The table reveals that in this case the offset of the line can be confirmed as having a non-zero value. In the case of the split run off the water which is drawn from the system early in the morning has been stored in the solar cylinder throughout the night, and has therefore had more opportunity to heat up by simple heat transfer from the tank surroundings. However, the value of A1' is still required to determine the efficiency of the system in Section 6.5. Table 6.4 contains the necessary result.

A1'	1.087 ± 0.032m^2

Table 6.4: Performance parameters for the AES system (split run off: simplified analysis model)

The larger uncertainties in the parameters estimated from the split run off data are a consequence of two effects. Figure 6.3 shows that, even with the revised averaging of solar radiation the fit to the proposed straight line model is less precise. Furthermore, data were gathered on fewer days using this run off schedule, and this allows the coefficients to be determined with a lower accuracy.

6.3 Characterising system electricity consumption

In order to obtain a full picture of the energy contribution from each system it is also necessary to assess how much electrical energy will be consumed over a typical year. Figure 6.4 shows the daily electricity consumption of the AES system for a single evening run off, again plotted as a function of incident solar radiation.

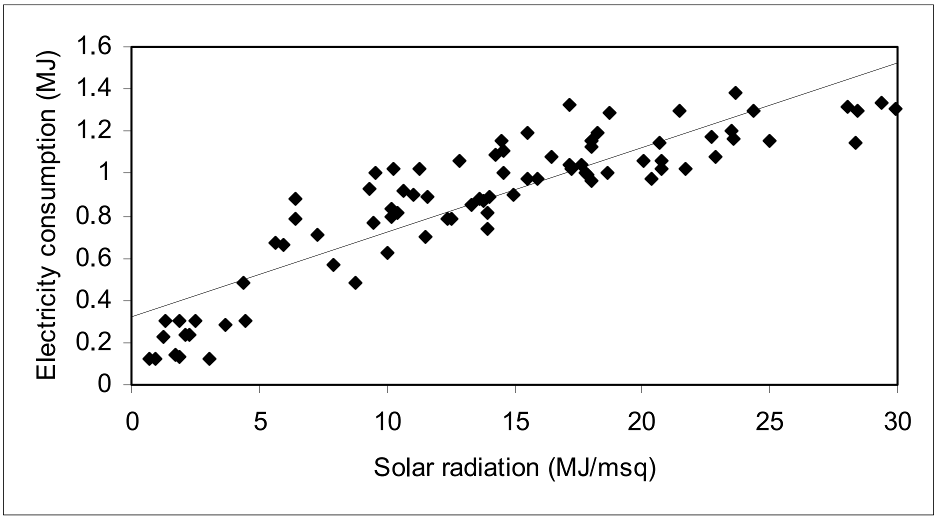


Figure 6.4: Daily electricity consumption of AES system as a function of solar

The linear relationship is not as good as that obtained for system output, although for many of the other systems it is significantly better than that shown in Figure 6.4. Table 6.5 shows the corresponding coefficients, denoted by E0 and E1.

E0	0.318 ± 0.072MJ
E1	0.040 ± 0.005m^2

Table 6.5: Electrical energy consumption parameters for the AES system

The uncertainties associated with these coefficients are larger than that of the solar performance parameters, a reflection of the poorer fit to the proposed straight line model. However the amount of energy being used is much smaller than the amount of hot water produced, and the overall error introduced is therefore small by comparison.

6.4 Extrapolating performance to a typical year

Armed with the two straight line relationships derived above it is possible to predict the output and electricity consumption of the system over a typical year. Figure 6.5 shows the 20 year average values for solar radiation on a south facing surface inclined at 30° for Kew, taken from [5].

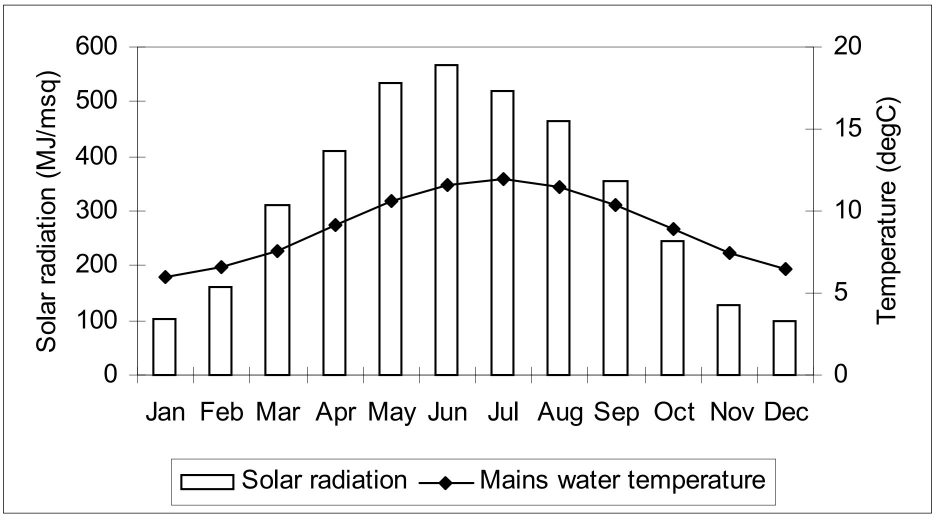


Figure 6.5: 20 year average data used for calculation of annual performance

Figure 6.5 also shows the assumed cold water inlet temperature. In keeping with the suggestions of the Feasibility Study this varies sinusoidally over the year about a mean value of 9°C with amplitude 3°C.

Table 6.6 shows the calculation of the energy requirement associated with a hot water load of 150litres/day, assuming a required delivery temperature of 55°C, and cold water supply temperature profile described above. The table also shows the predicted output of the system, calculated using the equation of the line fitted in Section 6.2. Although it was shown that for this particular case a simplified single parameter model could be used to predict system performance the two parameter model has been used, in order to ensure that the outputs of all systems are predicted in a consistent way. Finally the estimated system electricity consumption, obtained using the equation of the line fitted in Section 6.3, is also shown in the table.

	Cold water supply temperature (°C)	Hot water demand (MJ)	Incident solar (MJ/m^2)	Hot water production (MJ)	Electricity consumption (MJ)
JAN	6.0	938	96	113	14
FEB	6.6	837	167	195	16
MAR	7.6	908	308	357	22
APR	9.1	851	386	446	25
MAY	10.6	850	500	577	30
JUN	11.6	804	550	634	32
JUL	12.0	823	516	595	31
AUG	11.5	833	463	535	28
SEP	10.4	827	372	430	24
OCT	8.9	883	250	290	20
NOV	7.4	882	144	168	15
DEC	6.5	929	92	108	14
TOTAL		10 366	3842	4447	270

Table 6.6: Sample calculation of load, output and electricity consumption

The results of carrying out this calculation for each system are presented in Appendix C. The Appendix also contains the values of A0 and A1 for each system under both run off schedules, allowing similar calculations to be carried out using weather data from alternative locations. Figure 6.6 summarises the result of this calculation graphically. The corresponding version of Figure 6.6 for each system is also included in Appendix C.

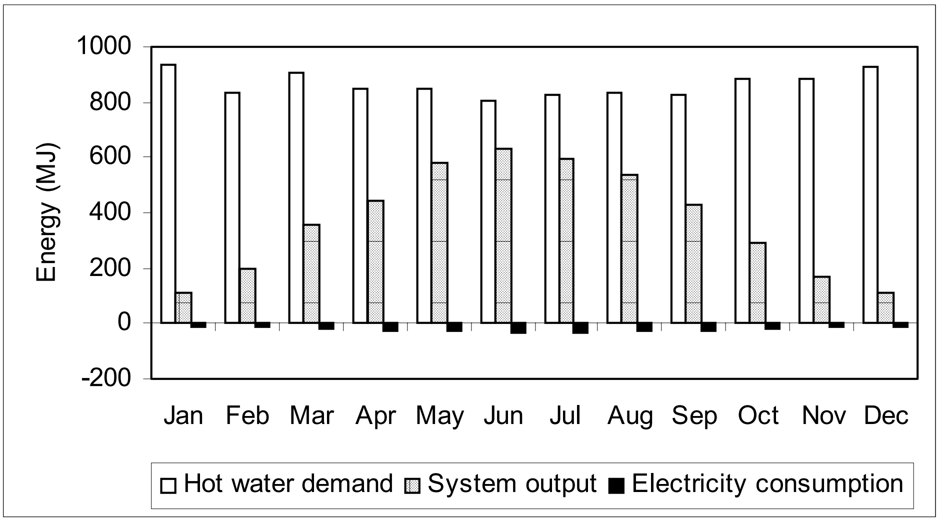


Figure 6.6: Estimated monthly system output and electricity consumption

6.5 Deriving system efficiency

An alternative interpretation of the simplified performance equation developed in Section 6.2 is in terms of system efficiency. This is normally defined as the ratio between the energy delivered by the system and the total energy incident on it:

$$\eta = Q_{out} / A\, Q_{solar}$$

where:

η is the system efficiency, and

A is the collector area.

Inspecting the simplified one parameter model described in Section 6.2 reveals that the efficiency could readily be calculated from the parameter derived when fitting that model, using:

$$\eta = A1' / A$$

This method of calculating the efficiency has the advantage that it provides a result directly from the measured performance data. However for systems which have significant values of the parameter A0 it does not always give results consistent with the predictions of annual performance. This is not surprising: for these systems the single parameter model and corresponding notion of a constant system efficiency are not strictly applicable. The problem is particularly apparent for one system whose annual output increases slightly for the split run off schedule but whose efficiency calculated in this way actually decreases slightly. To avoid such inconsistencies an alternative method has been used in which the values of Q_{out} and Q_{solar} used are simply those from the annual performance estimation carried out as described in the previous section. This gives results which are typically only one or two percentage points away from those derived by the more direct technique using A1', but which are completely consistent with the tabulated annual outputs.

There are a number of ways in which the collector area A can be calculated:

- the Gross area can be found from the overall dimensions of the collector. This is the critical dimension when determining how many collectors can be fitted into a given roof area. When used to calculate efficiency it provides less favourable results for collectors which require manifolding arrangements external to the collectors themselves. As a result it tends to penalise evacuated tube collectors,

- the Aperture area is the area through which solar radiation is actually transmitted into the system. Thus it excludes the area of any framing and manifold arrangements. Finally,

- the Absorber area is found by measuring the area which is available for the absorption of solar radiation. This area may bear no relation to the external dimensions of the collector, but if comparisons are to be made to a theoretical value calculated from absorber plate and cover properties then this is the most appropriate area on which to base the efficiency calculation.

The performance tables presented in Appendix C of this report include the Gross, Aperture and Absorber areas for each system. In view of the above discussion the efficiencies reported are derived using the system Gross and Absorber areas. Where the annual performance is normalised to unit collector area the Aperture area has been used as a median between these two extremes.

A problem of definition arises when calculating the Aperture and Absorber areas of the Solar Twin system. The photovoltaic panel which powers the system pump obscures part of the collector, and this section cannot therefore contribute to the direct heating of the water which circulates through it. It could be argued that the photovoltaic array is itself absorbing solar radiation, some of which is eventually transferred to the water stream via losses within the pump. However, the manufacturer has in the past excluded this section from the calculated Aperture and Absorber areas, and this is the approach adopted here. The impact of the assumption is small, reducing the areas by approximately 2%.

For the AES system analysed here the annual output was estimated to be 4447MJ when a single evening run off was used. The total solar incident over the year for which this performance was predicted is, from Table 6.6, 3842MJ/m^2. Reference to Appendix C reveals that the Gross area of this collector is 3.384m^2, and that the Absorber area is 2.964m^2. Inserting these figures into the equation which defines collector efficiency gives results of 34% based on Gross area and 39% based on Absorber area.

6.6 Analysis of errors

Any physical measurement inevitably contains sources of uncertainty, or ‘error’. Customarily these are divided into two categories: systematic and random errors [6].

Systematic errors stem from errors in the calibration of instruments, or the way in which those instruments have been applied to a particular measurement problem. In general they can be reduced by more careful calibration or installation. In Section 5 the systematic errors introduced by each of the sensors used on this project were detailed, and these are summarised below in Table 6.7.

Quantity measured	Systematic Error
Solar radiation	±2%
External temperature	±0.3°C
System electricity consumption	±1%
Hot water supply and delivery temperatures	±0.15°C at 0°C rising to ±0.35°C at 100°C *for each sensor*
Hot water volume	±2%

Table 6.7: Sensor accuracies

The uncertainty in the measurements of hot water supply and delivery temperatures requires some further consideration before it can be combined with the uncertainty in the flow measurement to yield the overall uncertainty in the energy produced by each system. The reason is that to calculate the overall uncertainty the measured temperature difference and flow are multiplied together. The uncertainty in the resulting product is given by the sum of the relative uncertainty in each quantity. For the flow measurement this relative uncertainty is simply ±2%, but for the temperature difference it is currently expressed in absolute terms.

To complicate matters further the absolute errors in the two temperature measurements are themselves a function of the temperatures being measured. It is clear that the higher these temperatures are, the worse will be the absolute errors. However, the relative error is worse at small temperature differences, as then it forms a larger part of the net reading. Table 6.8 shows a sample calculation of the total error when system output is determined with a delivery temperature of 15°C, the largest value typically encountered. Here a hot water supply temperature of only 35°C has been taken, again a pessimistic assumption.

Cold supply temperature (assumed 15°C)	±0.1725°C
Hot water delivery temperature (assumed 35°C)	±0.2200°C
Temperature rise	±0.3925°C
Relative error in temperature rise	±2.0%
Accuracy of flow measurement	±2.0%
OVERALL UNCERTAINTY	±4.0%

Table 6.8: Sample error calculation

Figure 6.7 shows the relative error as a function of hot water delivery temperature. Once again, the figure has been constructed assuming a supply temperature of 15°C, the largest value typically encountered, although it should be noted that the size of the error is relatively insensitive to this assumption.

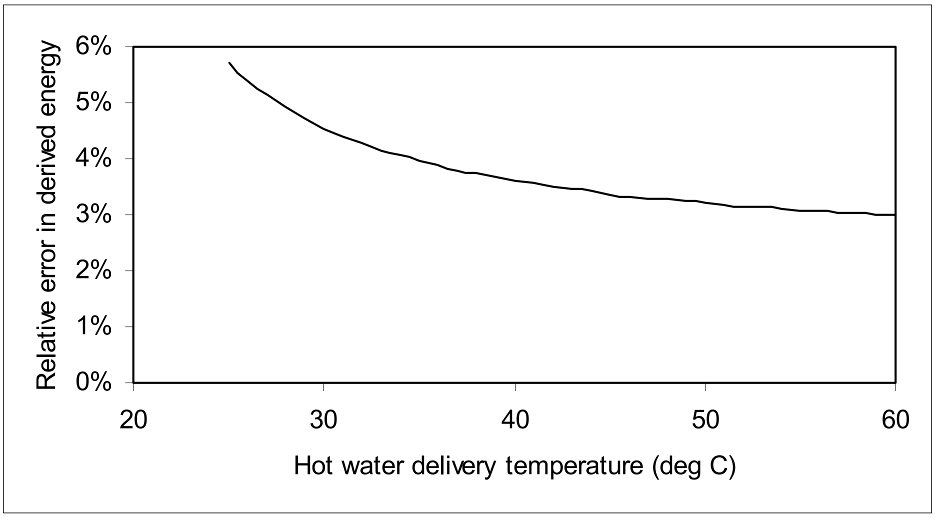


Figure 6.7: Error in derivation of energy delivered

As expected, the relative error becomes very large for small temperature rises: indeed, it must approach infinity as the temperature rise, and hence energy delivered, becomes close to zero. However the graph shows that for the hot water delivery temperatures typically provided by the systems the figure is generally less than 4%, and this is the value that will be used here.

The second source of uncertainty is random error. If the same quantity is measured repeatedly there will inevitably some small variations in the results obtained, and these obscure the exact result. In the analysis described here this causes uncertainties in the exact values of the parameters derived from the data, and examples of these have already been reported in Section 6.2, where we saw that the uncertainty in the derived parameter A1' (which is directly related to collector efficiency) was ±1.5% for the single evening run off data, and ±3.0% for the split run offs.

Random errors differ from systematic errors in that their effect can often be reduced by making a measurement many times, and averaging the results. Here that has been done by repeating the required measurements on many days, and the resulting reduction in uncertainty is reflected in the error bands already derived for the parameters A0, A1 and A1'. Such random errors will not be correlated with the systematic errors and when combining the two sources of uncertainty it is therefore appropriate to add them in quadrature. The total uncertainty in the result is given by:

$$\varepsilon_{total} = (\varepsilon_{systematic}^2 + \varepsilon_{random}^2)^{1/2}$$

where:

ε_{total} is the total uncertainty in the result,

$\varepsilon_{systematic}$ is the contribution from systematic sources of error, and

ε_{random} is the random error.

When evaluating the measurements of system output the overall uncertainties are therefore

$$\varepsilon_{total} = (4.0^2 + 1.5^2)^{1/2} = 4.3\%$$

and

$$\varepsilon_{total} = (4.0^2 + 3.0^2)^{1/2} = 5.0\%$$

respectively for the two run off patterns.

Finally, when the efficiency of each system is calculated the uncertainty in the measurement of solar radiation must be included as an additional source of systematic error. For the instrument used this is ±2%. This in turn increases the systematic error to ±6.0%, and the two overall uncertainty bands to ±6.2% and ±6.7% respectively.

7 RESULTS

In this section the performance of each of the eight systems, derived as described in the previous section, is summarised. Before that some general observations on the merits of side by side testing are presented, and the various problems encountered with the systems over the testing period are catalogued.

7.1 Technical issues arising from side by side testing

The principal reason for adopting a side by side approach to system testing is that it allows comparisons between systems to be made directly. Contrast this with previous studies (for example [7]) where different systems have been tested in actual operation, resulting in different run off patterns from each. Furthermore such tests are usually carried out at different locations or over different periods of time, and therefore the climate and solar geometry experienced by each system is also inevitably different.

Almost any test procedure will seek to parameterise the results obtained. This may be done just to condense the vast amount of information collected, to facilitate comparisons between systems or to allow extrapolation of the performance observed to other climate regimes. Inevitably the parameterisation will not be perfect, and will introduce uncertainties additional to those in the measurements themselves.

In a side by side test a number of the sources of these uncertainties are removed. For example run off schedules are standardised across all systems being tested, and all systems exposed to the same climate.

A final aspect of side by side testing is that it will normally be carried out in a purpose built facility, since it is unlikely that the required range of systems will be installed together in a real application. This in turn means that the test environment will be more highly controlled than in a field trial, which will again help to produce results which contain lower uncertainties.

In conclusion, side by side testing allows experimental uncertainties to be controlled to a level where it is much more likely that useful conclusions can be drawn from a test. At the same time they can retain the degree of realism which is necessary if the test results are to be widely accepted.

7.2 System malfunctions

Table 7.1 describes the minor problems with the systems which were encountered at or immediately after installation time.

System	Problem
ZEN	Printed circuit board supplied in system controller was from a defective batch. As a result system output was extremely low. The board was replaced with one from a later batch.
Riomay	The Riomay system uses six evacuated tubes which are mounted in a frame which contains the necessary manifold. One tube was installed upside down. This would have resulted in a reduction in system output of approximately 1/6. The problem was corrected by re-orienting the tube.
Filsol	The non-return valve provided with the system had become blocked with flux when it was pre-assembled onto the other components, making it impossible to obtain any flow through the system. The system output would therefore have been zero. The problem was corrected by replacing the faulty component.

Table 7.1: Problems encountered at installation time

The problem with the controller on the ZEN system was spotted when the faulty circuit board continually flashed an error code on the display. The problems with the Riomay installation were only identified when a representative of the company visited the installation. Finally, the problem with the Filsol non-return valve was detected when, during system commissioning, it proved impossible to obtain a reading on the flow tube which was installed in the collector loop. In summary, all of these problems would have been detected, and presumably corrected, as part of the normal installation and commissioning procedure.

A number of further minor problems were encountered after all of the systems had been commissioned, over the six month period for which they were in use. The data selection criteria described in Section 6.2 were designed to eliminate data from systems displaying problems, and these minor malfunctions do not therefore affect the estimation of system performance. The performance figures presented in the remainder of this section represent estimates of the energy outputs which would be obtained from systems which were working perfectly.

Table 7.2 summarises the problems encountered in operation.

System	Problem
Riomay	During a short power cut the system boiled. This caused the plastic tubing used to connect the manifold to the supply and return pipework to melt. This made the system impossible to re-pressurise and resulted in zero output. The pipework was replaced with copper. The non-return valve was then found to have no internal components. This meant that it was ineffective, and that reverse siphoning could have occurred at night, resulting in a loss of energy gathered during the day. It is not known whether the valve had been faulty since installation, or whether its internals had been dislodged during the boiling incident. The faulty valve was replaced.
Fieldway	The system pump failed after approximately two months operation, resulting in no flow through the collectors and consequently no useful output. It was replaced.
Thermomax	During a short power cut the system boiled over. When power was restored it was not possible to repressurise it. This turned out to be due to a leaking overpressure release valve, which was duly replaced.

Table 7.2: Problems encountered during first six months operation

In a normal installation the depressurisation of the Riomay and Thermomax systems would be readily detected by checking the reading on the system pressure gauge.

The lack of flow in the collector loop caused by the failure of the Fieldway pump could have been detected if a flow tube had been installed as part of this system, but unfortunately it had not. The implication of this is that in a normal installation, where there is no detailed performance monitoring, the problem could have gone unnoticed for a considerable time. This is a problem which could have afflicted any of the systems, and the installation of a flow tube would therefore be a valuable addition to all of those which do not currently feature a way of detecting this type of failure.

7.3 Annual system outputs

In order to be able to compare the performance of the eight systems it is clearly desirable to produce a single 'figure of merit' which summarises the net benefit provided by each system. One way of doing this would be to deduct the electricity consumed by the system from the hot water it provides. However this implies that energy transferred to water has the same value as the peak rate electricity used to operate the system pumps. There are a number of arguments which suggest that the electricity should be accorded rather higher value than the heated water:

- CO_2 emissions: the CO_2 production associated with electrical energy is typically 0.188kg/MJ, whereas for gas it is 0.052kg/MJ [8]. To obtain the corresponding value for hot water heated by gas a boiler efficiency of 70% is assumed [8], giving a net emission of 0.074kg/MJ of hot water produced. On this basis the electricity used to run the pump is 2.5× more 'expensive' than any hot water produced. This factor only applies if gas is the alternative fuel. If hot water was to be produced using electricity the ratio would of course be unity.

- Cost: At the time of writing the cost of peak rate electricity is typically £16.50/GJ whereas the cost of gas is only £3.70/GJ. Allowing for boiler efficiency as before the electricity used to run the pump is therefore 3.1× more expensive than hot water produced from gas. If hot water is heated using off peak electricity the associated cost is £6.80/GJ giving a cost ratio of 2.4× although in this case some allowance should probably be made for storage tank losses.

- Primary energy consumption: The generation and transmission of electricity inevitably involves losses. Typically the primary energy used is approximately 2.5× the electricity actually delivered to the consumer.

In view of these arguments it is perfectly reasonable to subtract 2½× the estimated electrical energy consumption from the total system output, to yield a value representing the 'net benefit' offered by each system. Each column on Figure 7.1 shows total system output, with the dividing line across each column showing system output minus 2½× the electrical energy consumption. Thus comparing the overall height of each bar allows the total output of each system to be assessed, but comparing the positions of the dividing lines gives a more accurate representation of the overall environmental benefit. Note that because the Solar Twin system is powered by its integral photo-voltaic array it consumes no electrical energy from external sources, and for this system the two lines coincide.

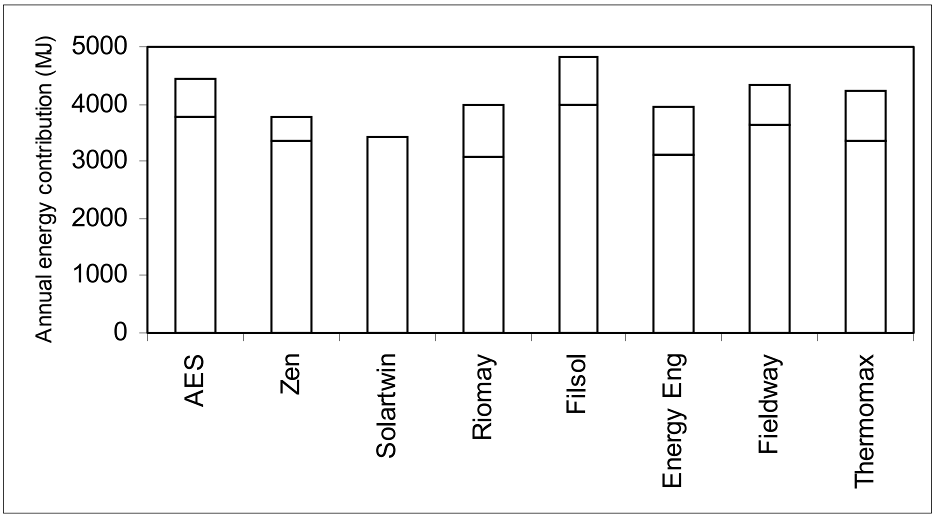


Figure 7.1: Estimated annual performance for each system
(single evening run off)

The figure demonstrates very clearly the impact of considering parasitic energy consumption. As expected the effect is most pronounced for the Solar Twin system, where the parasitic energy consumption is zero. When total hot water output is considered this system provides the lowest contribution. However when parasitic energy consumption is taken into account it moves from eighth place to fourth place: a clear demonstration of how important it is to consider all energy paths before assessing systems.

The position of the dividing line, expressed in MJ on Figure 7.1, can be interpreted directly in terms of the primary energy saved by each system, when gas would otherwise have been used to heat the water provided. This can also be expressed in terms of the net reduction in CO_2 emission. Using the values presented above yields:

$$RCO_2 = 0.074 \times Q_{out} - 0.188 \times E$$

where:

RCO_2 is the reduction in CO_2 emission in kg and

E is the system electricity consumption in MJ.

The resulting values are tabulated for all the systems in Appendix C.

Figure 7.2 shows the results for the split run off sequence.

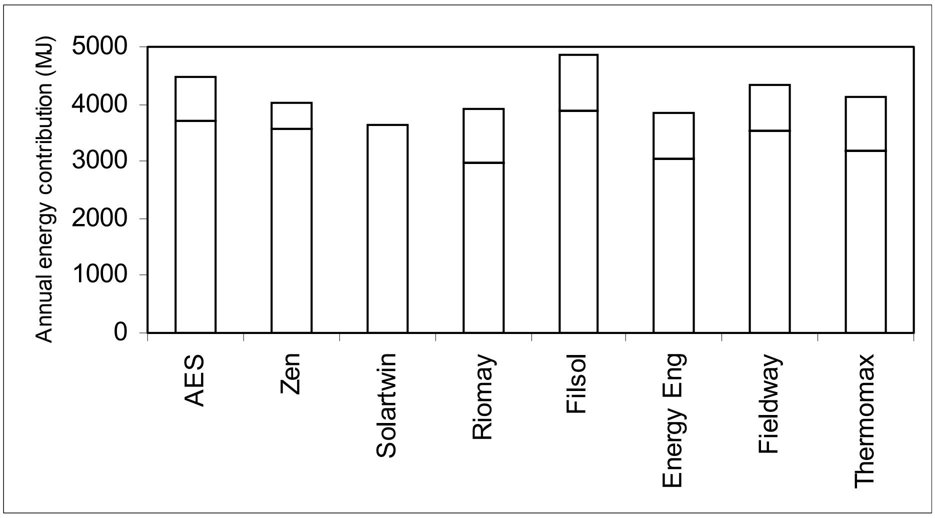


Figure 7.2: Estimated annual performance for each system
(split run off schedule)

Once again, including parasitic energy in the assessment makes a significant difference. In this case the Solar Twin system moves from eighth to third place in the ranking.

The figure shows that most of the systems produce slightly less energy when the split run off schedule is used. This is initially a surprising result: it might be expected that running off water early in the day and introducing cold water into the tank would give the system the chance to operate at a higher efficiency during the afternoon, and result in increased output. However, the run off process is likely to disrupt stratification in the tank, which to some extent will reduce this effect. Furthermore, the requirement for hot water first thing in the morning does mean that some must be stored overnight, with corresponding losses. The results presented here indicate that taken together these two effects are just sufficient to overcome the benefits of operation at higher efficiency during the afternoon.

The one exception to this rule is the ZEN system, which actually performs better when faced with the split run off schedule. The reason for this is that the storage tank which is integrated with the ZEN system has a capacity of only 140litres. When a single draw off of 150litres is made in the evening the last 10litres will be effectively at incoming mains temperature, and in comparison with systems with a storage capacity in excess of 150litres the output of the system will be reduced by one part in fifteen, or about 6%. However, when the draw off is spread throughout the day the smaller tank of the ZEN system gives faster recovery and, in contrast to the other systems, performance improves.

7.4 System efficiencies

The principal aim of this project is to establish the energy output expected from each of the systems under test over a year of normal operation, and that information was presented in the previous section. However, it is also of interest to normalise this value by system area. In this way it is possible to tell whether systems which have done well have done so by virtue of their high efficiency, or because a large area of collector has been installed.

The efficiency of each system has been derived as described in Section 6.5. The figure below shows the results for the single evening run off based on Gross system area.

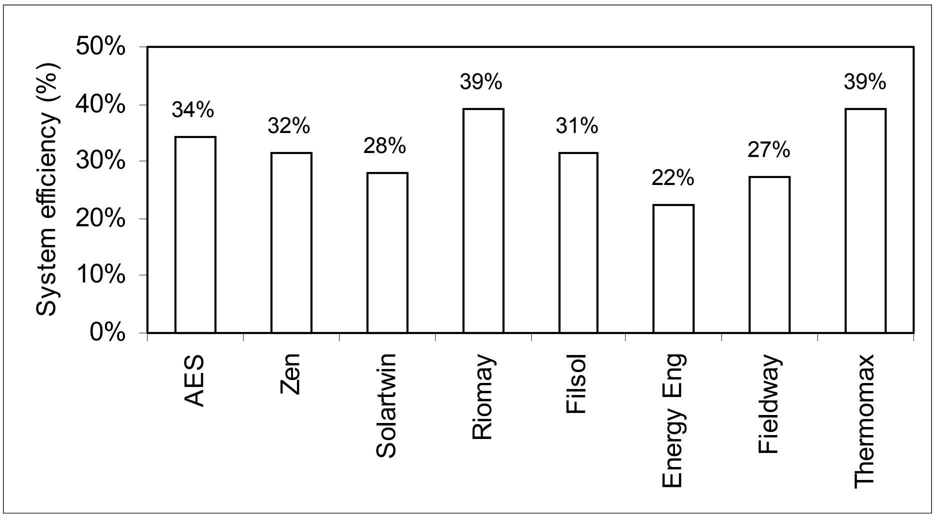


Figure 7.3: System efficiencies based on Gross area (single evening run off)

It is important to remember that this is a thermal efficiency, and so by definition it is based on gross system output. If an allowance was made for parasitic energy consumption the relative efficiency of the Solar Twin system would rise to a value closer to its counterparts.

Figure 7.4 overleaf shows the corresponding results based on Absorber area.

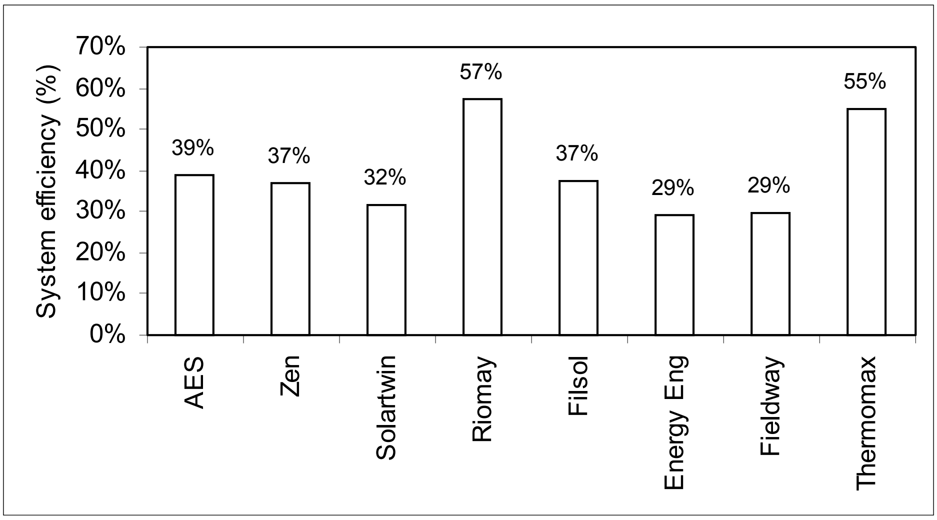


Figure 7.4: System efficiencies based on Absorber area (single evening run off)

As expected, when the efficiencies are calculated using Absorber area there is little change in the results for the flat plate collectors. There is, however, a significant increase in the results for the two evacuated tubes.

Since the system efficiencies are derived from the estimates of annual output presented in the previous section the trends observed when the split run off schedule is used are entirely consistent with the results presented there.

8 CONCLUSIONS

The results presented in this report have demonstrated that the side by side test facility developed for this project is capable of providing consistent measurements of the performance of all the systems installed on it. A few minor problems occurred with some systems, but all were quickly rectified. Data from the periods when these problems occurred have been omitted from the analysis described here, and the performance figures presented therefore represent estimates of the benefits which would be obtained from systems which were working perfectly.

The tests carried out have shown that all of the systems are capable of producing a useful amount of hot water under UK climate. When the load consists of a single 150litre draw off early in the evening the extrapolated annual hot water production ranges from 3440 to 4820MJ. When the load is spread over the course of each day the corresponding range is 3620 to 4860MJ.

In assessing the value of the energy provided by each system it has proved vitally important to take into account the parasitic energy used by most to power controllers and pumps. The extrapolated annual parasitic energy consumption ranges from zero to 390MJ. Including this in the appraisal of the systems significantly changes the ranking of their performance, with one system moving from eighth to third place.

As expected expressing these results in terms of collector efficiency reveals that the two evacuated tube designs operate at a higher efficiency than their flat plate counterparts. However they do not provide significantly more or less energy over the course of the year, and fall in the middle of the overall range of system outputs. This implies that the relative sizes of the systems almost exactly compensate for differences in system performance.

More surprising is the relatively small sensitivity to the pattern of water draw off over the course of the day. Conflicting factors which affect the outputs of the systems have been identified: a draw off pattern which requires water early in the morning requires that some hot water is stored overnight, with corresponding losses, but at the same time it gives lower tank temperatures during the day, allowing the collectors to operate more effectively. In all cases these two effects almost exactly cancel out, leading to slightly higher outputs for some systems and slightly lower for others when changing from a single evening draw off to one distributed throughout the day.

As well as these immediately interesting and useful results the project has produced a large quantity of high quality performance data for all eight systems. It is hoped that these data sets will be of value to the system manufacturers as they develop their products and to other researchers in future studies.

The goal of this project was to compare the energy performance of eight modern solar water heating systems. In assessing the mass of results presented it is important to remember that the amount of energy delivered is not the only criterion to be considered when selecting a system. Long term reliability, possible degradation of performance over the lifetime of a system and resistance to vandalism or accidental breakage may all be important in a given application. The assessment of these aspects of performance was outside the scope of this project, but their consideration may be vital for specific installations.

9 RECOMMENDATIONS

This project set out to measure the performance of eight commercially available solar water heating systems, in the configuration in which they would normally be installed. It is therefore outside the brief of the project to make recommendations about the installation of the systems. However, one potentially useful observation has emerged:

- Some of the systems tested featured a flow tube to give a visual indication that there is flow through a collector. The ZEN system incorporates an electronic flow sensor, and the controller flashes an error message if the flow through the collector becomes abnormally low. In the course of this project one problem, a blocked non-return valve, was rapidly diagnosed at installation time thanks to the presence of a flow tube. A second problem, a failed pump, developed on a system which was not equipped with such an indicator and was only diagnosed after a period of several days when the monitored data was analysed. The implication of this is that in a normal installation, where there is no detailed performance monitoring, the problem may have gone unnoticed for a considerable time.

Two recommendations emerge from the project regarding the monitoring of solar water heating systems:

- The use of independent flowmeters to measure the actual volume of water run off from each system was originally justified on the grounds that if the flow varied during the run off it would not be possible to calculate the associated energy gain with precision. In fact the run off rate remained remarkably constant as water was taken from each system. Where the flowmeters really proved their worth was by providing a check that the correct overall amount of water was being run off each day. This in turn allowed problems with the valves used to seal the metering tanks to be quickly diagnosed and corrected, limiting the resulting loss of data to only a few days. As well as this redundancy in the flow measurement this project provided redundancy in the measurement of cold water supply measurement as two separate measurements were made in each equipment enclosure. Comparing these two measurements provided a further check that the temperature sensors and their associated data logging equipment were working consistently. The value of these checks is reflected in the very small fraction of data which was lost due to problems with the collector test rig itself. It is clearly a recommendation for future projects of this type that, subject to cost limits, as much redundancy as possible should be built in.

- It is clearly important to consider parasitic energy consumption when ranking systems, and as this can be added to any monitoring scheme for a relatively small cost it should clearly be considered essential in future monitoring exercises.

The remaining recommendations concern further work, which could readily be carried out now that the test facility has been developed:

- As discussed in the previous section the tests have demonstrated that the performance of the systems is relatively insensitive to the pattern of run off. However, it is highly likely that their outputs will vary significantly if the actual run off volume is varied. It is probable that many owners of these systems use more hot water on or after a sunny day, in order to maximise their savings. Further work could be carried out with the existing facility in its current form to investigate this.

- The tests carried out here have produced results for the situation where the solar cylinder is unheated. This is equivalent to assuming that the solar cylinder is used as a preheat tank to a second cylinder, that auxiliary heating is provided by an instantaneous source, or that the householder switches off auxiliary heating and relies solely on solar heated water. The latter is unlikely to be the case throughout the year. In all other cases auxiliary heat will be added to the solar cylinder itself. This will disrupt stratification, and result in the collector being supplied from a higher temperature, with a corresponding drop in efficiency. It would be possible to install electric immersion heaters in most of the cylinders currently in use, and use metered electricity as an auxiliary heat source in order to assess the impact of these effects. This would give a useful indication of the applicability of the current results to installations with integrated auxiliary heating.

- The tests carried out over the course of this project set out to establish the energy gain available from the systems over a typical year. There are both ISO and CEN standards for carrying out such tests. These are designed to produce consistent and repeatable results, and this has been demonstrated by ‘round Robin’ testing of systems at different test institutes. Following the recommendations of the project Feasibility Study [1] the work described in this report was not carried out in accordance with these standards. Indeed, to carry out tests to these standards on eight systems simultaneously would be a daunting task, and one in which would carry a very high degree of technical risk. However, it would be possible to upgrade part of the existing test facility to allow tests in accordance with the ISO or CEN specification to be carried out on, say, two of the systems. This would allow a comparison to be made with the existing results for those systems. If the comparison was close, and there is no reason to believe that it should not be, it would lend considerable further strength to all of the results presented in this report.

REFERENCES

[1] Feasibility Study for Comparative System Testing. J Kenna. ESD Ltd. Report number ETSU S/P3/00268/REP. 1999.

[2] ISO Standard 9459-2. Solar heating – Domestic water heating systems – Part 2: Outdoor test methods for system characterisation and yearly performance prediction of solar-only systems. 1995.

[3] ISO Standard 9459-5. Solar heating – Domestic water heating systems – Part 5: System performance characterisation by means of whole-system tests and computer simulation. 1995.

[4] BS6700. Design, installation, testing and maintenance of services supplying water for domestic use within buildings and their curtilages. 1997.

[5] Designers' handbook of UK data for Solar Energy applications. Prof John Page and Ralph Lebens. Report number ETSU S-1134. 1984.

[6] An Introduction to Error Analysis. J R Taylor. 1992.

[7] Analysis of performance data from four active solar water heating installations. C Martin. Energy Monitoring Company Ltd. Report number ETSU S/P3/00275/REP. 2001.

[8] The Government's Standard Assessment Procedure for energy rating of dwellings. Energy Efficiency Office. Department of the Environment. 1994.

APPENDIX A: DATA ORGANISATION AND FORMAT

The disk which accompanies this report contains all of the data gathered during the project. The purpose of this Appendix is to allow anyone wishing to carry out further analysis to make use of that data.

A1 Meteorological data

The meteorological data collected during the project is in a file called MET.TXT. It consists of fifteen minute records of solar radiation level in the plane of the collectors and external air temperature.

Solar radiation has been measured every five seconds, and the results averaged over fifteen minute periods. The averages are recorded on a preceding time step basis: the value recorded with time stamp 15:00:00 is the average from 14:45:05 through to 15:00:00. External ambient temperature was measured every fifteen minutes and recorded directly.

Table A1 describes how the values on each line, which are delimited by tab characters, are interpreted.

Entry	Quantity	Units
1	Date	DD/MM/YYYY
2	Time	HH:MM:SS
3	Solar radiation	W/m^2
4	External air temperature	°C

Table A1: Format of recorded meteorological data

A2 System performance data

Data from each system have been placed in a separate file. The files are named using the following convention:

SYS N . TXT

where:

SYS indicates that the file contains system data,

N is the system identifier. Eight of these are used:

1: AES

2: ZEN

3: Solar Twin

4: Riomay

5: Filsol

6: Energy Engineering

7: Fieldway

8: Thermomax

The data format is summarised in Table A2.

Entry	Quantity	Units
1	Date	DD/MM/YYYY
2	Time	HH:MM:SS
3	Record identifier (=0 for 15 minute record 1 for run off data)	
Record type 0		
4	Electricity consumption	Wh
5	Shed temperature	°C
Record type 1		
4	Water supply temperature	°C
5	Water delivery temperature	°C
6	Water volume flow	litres

Table A2: Format of system data files

<u>A3 Dates of data used in analysis</u>

The file DATES.TXT contains two lists of dates. The first contains the days which were used to derive the performance of the systems under the single evening run off schedule, and the second the dates used to analyse the split run off performance.

APPENDIX B: PHYSICAL PROPERTIES OF WATER

To calculate the energy associated with a given volume of hot water production it is necessary to know the density and specific heat capacity of water as a function of temperature. Figure B1 shows how the density of water varies with temperature, using data taken from [B1].

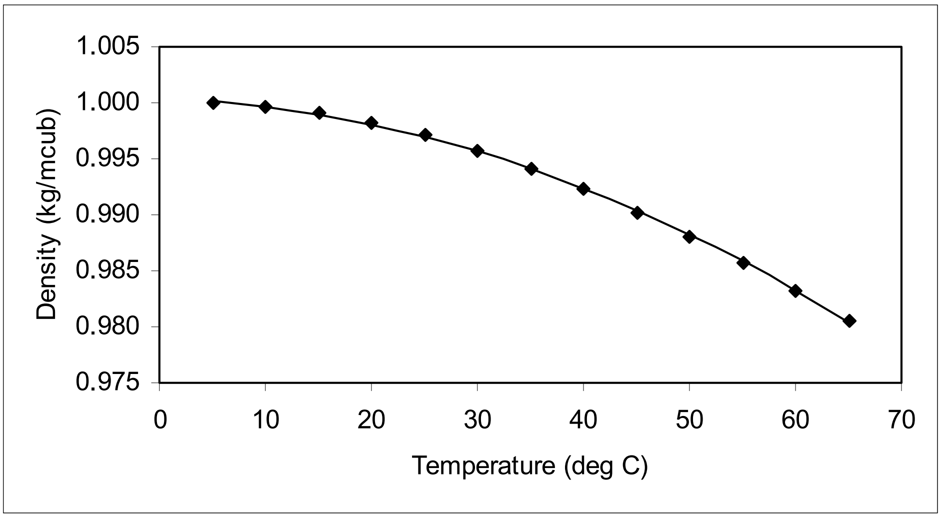


Figure B1: Density of water as a function of temperature

A polynomial has been fitted to the data, and the resulting curve is also shown on the graph. The expression for the density of water is:

$$\rho = 1.000496154 - 3.7055E\text{-}05\ T - 4.1802E\text{-}06\ T^2$$

where:

ρ is the density in kg/m^3, and

T is the temperature in °C.

Figure B2 shows how the specific heat capacity varies with temperature, again using data taken from [B1].

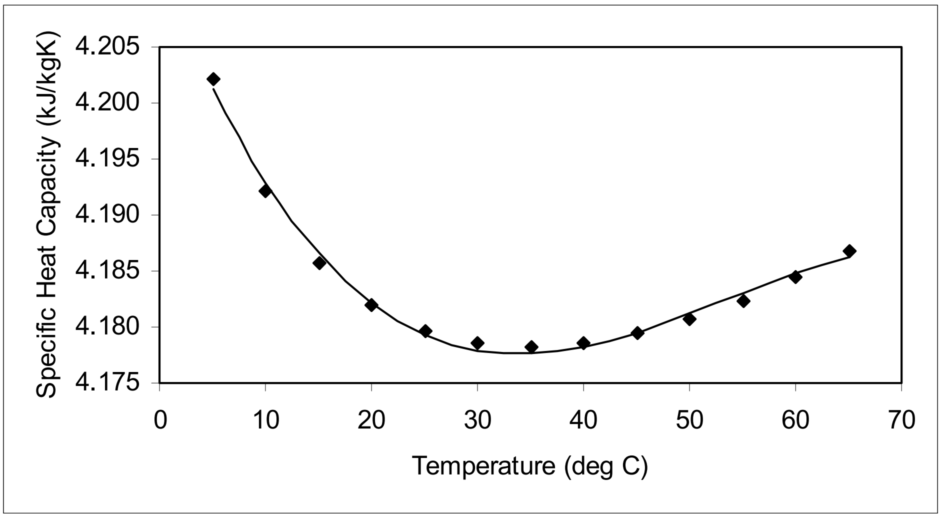


Figure B2: Specific heat capacity of water as a function of temperature

Once again a polynomial has been fitted to the data, and the resulting curve is also shown on the graph. The expression for the specific heat capacity of water is:

$$S = 4.2121 - 0.0024054\,T + 5.19456E\text{-}05\,T^2 - 3.2424E\text{-}07\,T^3$$

where:

S is the specific heat capacity in $kJkg^{-1}K^{-1}$.

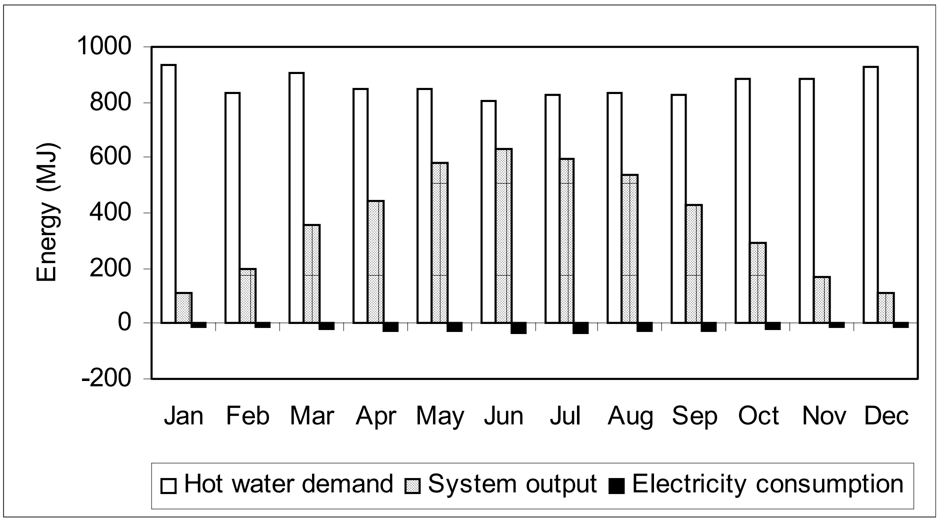
REFERENCE

[B1] Weast R C, Astle M J and Beyer W H. CRC Handbook of Chemistry and Physics. 67th Edition. 1987.

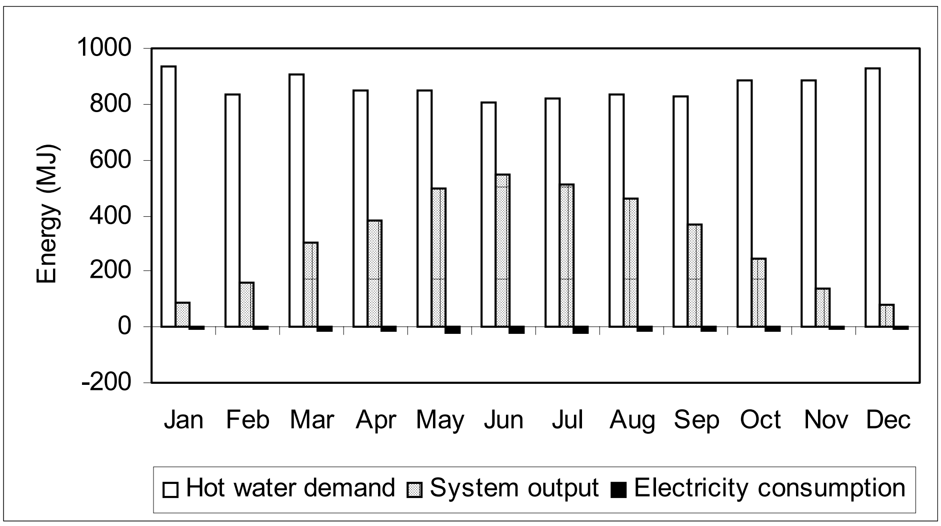
APPENDIX C: DESCRIPTION OF SYSTEMS AND SUMMARY RESULTS

The first eight tables in this Appendix give details of the participating system manufacturers, and summarise the results of analysing the measured performance of each system as described in Sections 6 and 7 of the main report. The final table contains explanatory notes which are common to the analysis applied to all eight systems.

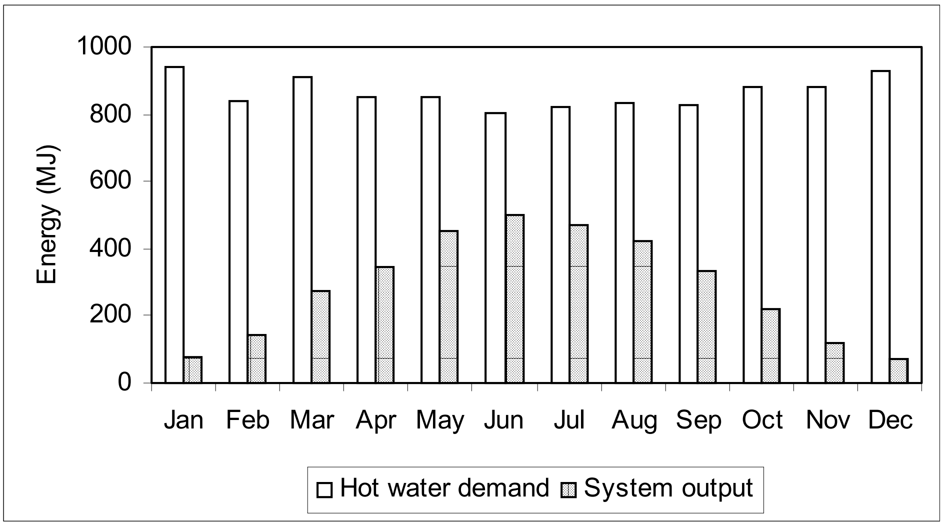
MANUFACTURER	Name	AES Ltd	
	Address	AES Building Lea Road Forres Scotland IV36 1AU	
	Telephone	+44 (0) 1309 676911	
	Fax	+44 (0) 1309 671086	
	e-mail	info@aessolar.co.uk	
SYSTEM	Model name	AES Type H Collector	
	Serial number	n/a	
	System type	Flat plate	
	Gross area	3.384m^2	
	Aperture area	3.068m^2	
	Absorber area	2.964m^2	
COST	Component cost	£ 1155 + VAT	
	Installed cost	£ 1885 + VAT	
PERFORMANCE PARAMETERS(1)		Single run off(2)	Split run off(3)
	A0	0.10±0.57MJ	1.85±1.14MJ
	A1	1.148±0.036m^2	0.985±0.069m^2
	E0	0.318±0.072MJ	0.549±0.056M J
	E1	0.040±0.005m^2	0.027±0.007m^2
EXTRAPOLATED ANNUAL PERFORMANCE	System efficiency(4)	34% (39%)	34% (39%)
	Estimated annual output(5)	4447MJ (1449MJ/m^2)	4461MJ (1454MJ/m^2)
	Estimated annual electricity consumption(5)	270MJ (88MJ/m^2)	304MJ (99MJ/m^2)
	Estimated annual CO_2 reduction(5)	278kg (91kg/m^2)	273kg (89kg/m^2)



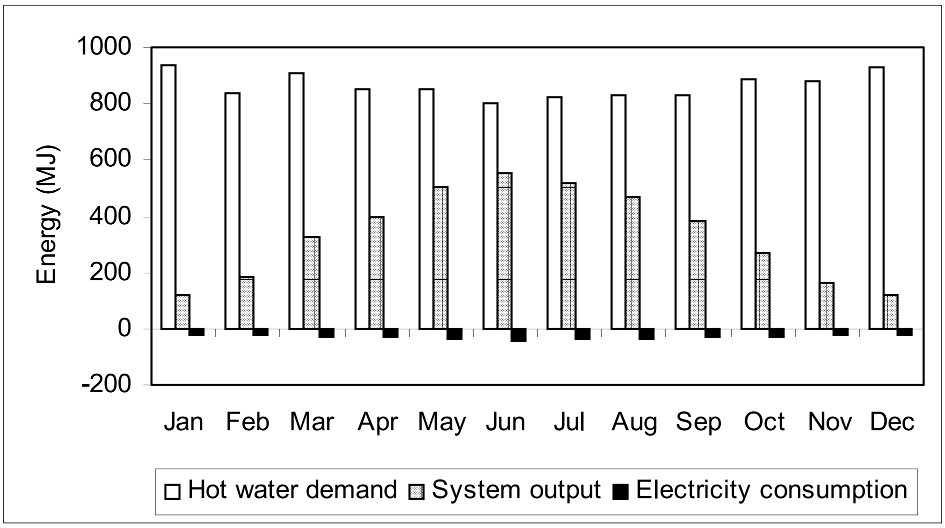
MANUFACTURER	Name	AES Ltd	
	Address	AES Building Lea Road Forres Scotland IV36 1AU	
	Telephone	+44 (0) 1309 676911	
	Fax	+44 (0) 1309 671086	
	e-mail	info@aessolar.co.uk	
SYSTEM	Model name	ZEN Type D collector	
	Serial number	9900229.001/01.4	
	System type	Flat plate	
	Gross area	3.100m^2	
	Aperture area	2.755m^2	
	Absorber area	2.656m^2	
COST	Component cost	£1345 + VAT	
	Installed cost	£2095 + VAT	
PERFORMANCE PARAMETERS(1)		Single run off(2)	Split run off(3)
	A0	-0.38±0.50MJ	0.81±1.11MJ
	A1	1.106±0.033m^2	0.968±0.067m^2
	E0	0.197±0.050MJ	0.305±0.036M J
	E1	0.022±0.003m^2	0.018±0.004m^2
EXTRAPOLATED ANNUAL PERFORMANCE	System efficiency(4)	32% (37%)	34% (39%)
	Estimated annual output(5)	3764MJ (1366MJ/m^2)	4018MJ (1458MJ/m^2)
	Estimated annual electricity consumption(5)	158MJ (57MJ/m^2)	179MJ (65MJ/m^2)
	Estimated annual CO_2 reduction(5)	249kg (90kg/m^2)	264kg (96kg/m^2)



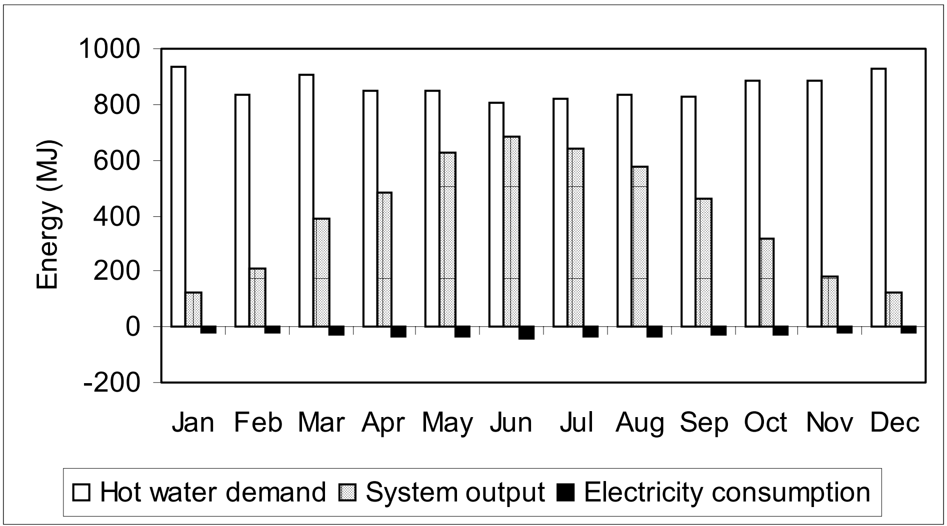
MANUFACTURER	Name	Solar Twin Ltd	
	Address	15 King Street Chester CH1 2AH	
	Telephone	+44 (0) 1244 403407	
	Fax	+44 (0) 1244 403654	
	e-mail	hi@solartwin.com	
SYSTEM	Model name	ST1200/2400a	
	Serial number	183809	
	System type	Flat plate	
	Gross area	3.187m^2	
	Aperture area	2.828m^2	
	Absorber area	2.828m^2	
COST	Component cost	£ 1264 + VAT	
	Installed cost	£ 2356 + VAT	
PERFORMANCE PARAMETERS(1)		Single run off(2)	Split run off(3)
	A0	-0.45±0.38MJ	1.84±1.12MJ
	A1	0.937±0.025m^2	0.768±0.067m^2
	E0	0.000MJ	0.000MJ
	E1	0.000m^2	0.000m^2
EXTRAPOLATED ANNUAL PERFORMANCE	System efficiency(4)	28% (32%)	30% (33%)
	Estimated annual output(5)	3436MJ (1215MJ/m^2)	3624MJ (1282MJ/m^2)
	Estimated annual electricity consumption(5)	0MJ (0MJ/m^2)	0MJ (0MJ/m^2)
	Estimated annual CO_2 reduction(5)	254kg (90kg/m^2)	268kg (95kg/m^2)



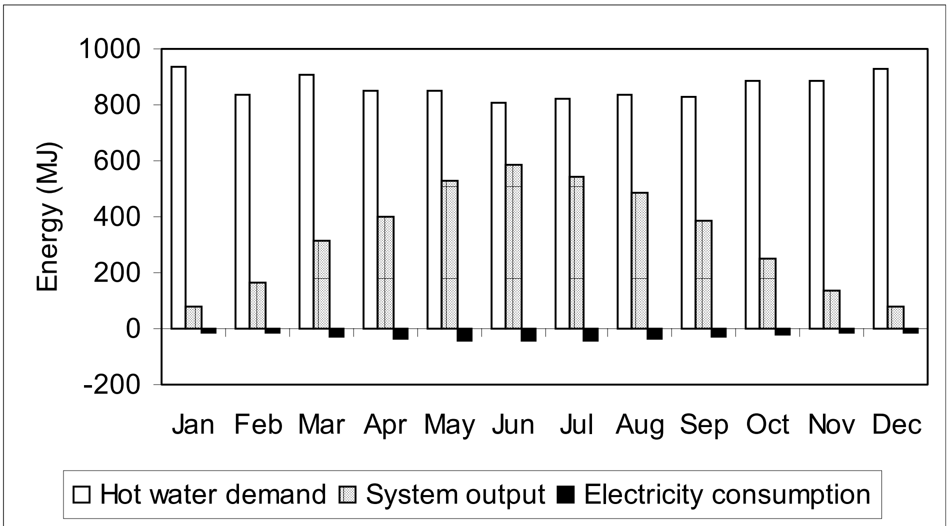
MANUFACTURER	Name	Riomay Energy Consultants	
	Address	1 Birch Road Eastbourne East Sussex BN23 6PL	
	Telephone	+44 (0) 1323 648641	
	Fax	+44 (0) 1323 720682	
	e-mail	tonybook@pavilion.co.uk	
SYSTEM	Model name	Suntube	
	Serial number	n/a	
	System type	Evacuated tube	
	Gross area	2.653m^2	
	Aperture area	2.021m^2	
	Absorber area	1.820m^2	
COST	Component cost	£ 1600 + VAT	
	Installed cost	£ 2500 + VAT	
PERFORMANCE PARAMETERS(1)		Single run off(2)	Split run off(3)
	A0	0.94±0.48MJ	2.95±1.03MJ
	A1	0.950±0.032m^2	0.743±0.060m^2
	E0	0.508±0.064MJ	0.059±0.164MJ
	E1	0.046±0.004m^2	0.093±0.019m^2
EXTRAPOLATED ANNUAL PERFORMANCE	System efficiency(4)	39% (57%)	39% (56%)
	Estimated annual output(5)	3995MJ (1977MJ/m^2)	3931MJ (1945MJ/m^2)
	Estimated annual electricity consumption(5)	363MJ (180MJ/m^2)	380MJ (188MJ/m^2)
	Estimated annual CO_2 reduction(5)	227kg (113kg/m^2)	219kg (109kg/m^2)



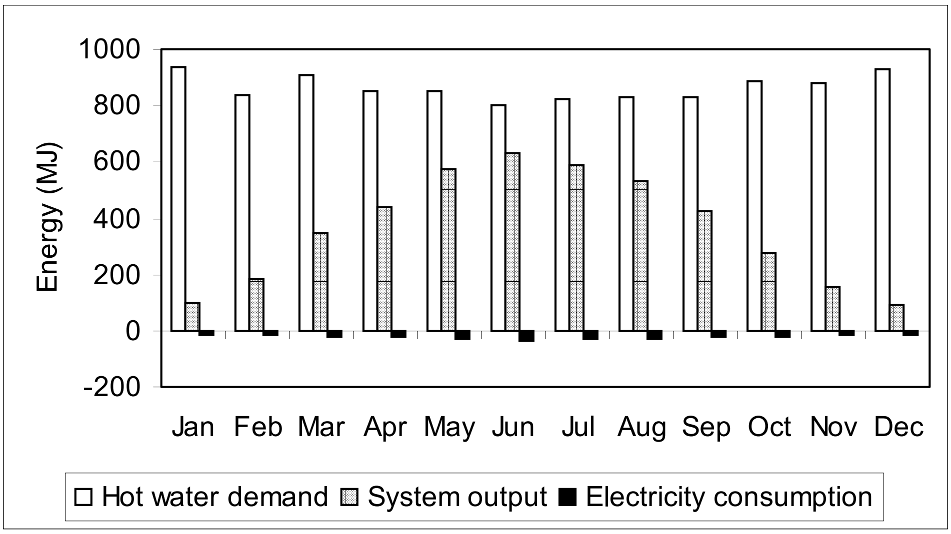
MANUFACTURER	Name	Filsol Ltd	
	Address	Unit 15 Ponthenri Ind Estate Ponthenri Llanelli Carmarthenshire SA15 5RA	
	Telephone	+44 (0) 1269 860229	
	Fax	+44 (0) 1269 860979	
	e-mail	john.blower@filsol.co.uk	
SYSTEM	Model name	n/a	
	Serial number	n/a	
	System type	Flat plate	
	Gross area	3.998m^2	
	Aperture area	3.417m^2	
	Absorber area	3.345m^2	
COST	Component cost	£ 1355 + VAT	
	Installed cost	£ 2050 + VAT	
PERFORMANCE PARAMETERS(1)		Single run off(2)	Split run off(3)
	A0	0.25±0.54MJ	2.57±1.19MJ
	A1	1.230±0.035m^2	1.022±0.072m^2
	E0	0.429±0.088MJ	0.769±0.069M J
	E1	0.048±0.006m^2	0.029±0.008m^2
EXTRAPOLATED ANNUAL PERFORMANCE	System efficiency(4)	31% (37%)	32% (38%)
	Estimated annual output(5)	4819MJ (1410MJ/m^2)	4864MJ (1424MJ/m^2)
	Estimated annual electricity consumption(5)	340MJ (100MJ/m^2)	393MJ (115MJ/m^2)
	Estimated annual CO_2 reduction(5)	293kg (86kg/m^2)	286kg (84kg/m^2)



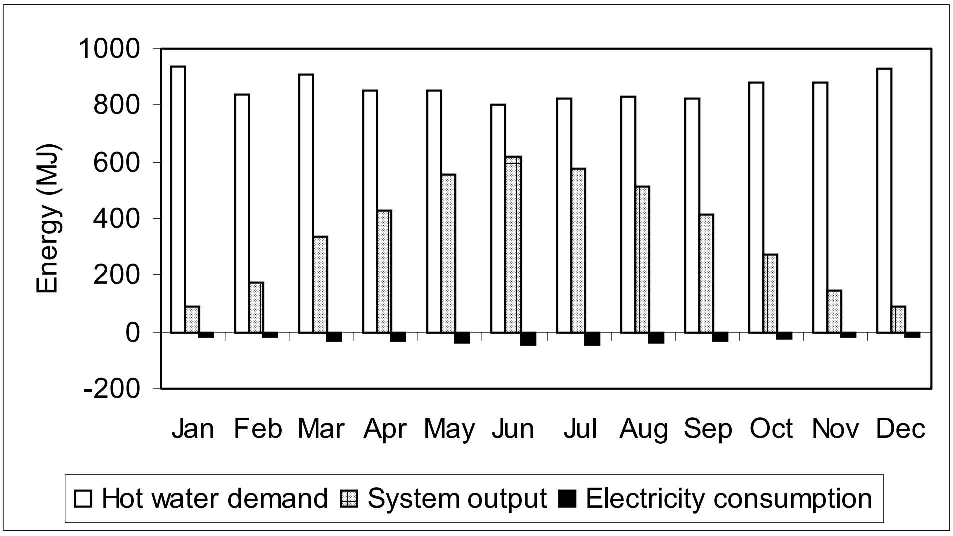
MANUFACTURER	Name	Energy Engineering	
	Address	Herons Reach Cound Moor Shrewsbury Shropshire SY5 6BB	
	Telephone	+44 (0) 1694 731648	
	Fax	+44 (0) 1694 731696	
	e-mail	energyengineering@btinternet.com	
SYSTEM	Model name	n/a	
	Serial number	n/a	
	System type	Flat plate	
	Gross area	4.594m^2	
	Aperture area	4.160m^2	
	Absorber area	3.531m^2	
COST	Component cost	n/a	
	Installed cost	n/a	
PERFORMANCE PARAMETERS[(1)]		Single run off[(2)]	Split run off[(3)]
	A0	-0.77±0.54MJ	0.41±1.09MJ
	A1	1.103±0.035m^2	0.964±0.066m^2
	E0	0.234±0.082MJ	0.365±0.074MJ
	E1	0.053±0.005m^2	0.046±0.009m^2
EXTRAPOLATED ANNUAL PERFORMANCE	System efficiency[(4)]	22% (29%)	22% (28%)
	Estimated annual output[(5)]	3954MJ (951MJ/m^2)	3853MJ (926MJ/m^2)
	Estimated annual electricity consumption[(5)]	340MJ (82MJ/m^2)	323MJ (78MJ/m^2)
	Estimated annual CO_2 reduction[(5)]	229kg (55kg/m^2)	224kg (54kg/m^2)



MANUFACTURER	Name	Fieldway Ltd	
	Address	Croft Road Crowborough East Sussex TN6 1DL	
	Telephone	+44 (0) 1892 655782	
	Fax	+44 (0) 1892 655792	
	e-mail	n/a	
SYSTEM	Model name	n/a	
	Serial number	n/a	
	System type	Flat plate	
	Gross area	4.114m^2	
	Aperture area	3.828m^2	
	Absorber area	3.828m^2	
COST	Component cost	n/a	
	Installed cost	n/a	
PERFORMANCE PARAMETERS[1]		Single run off[2]	Split run off[3]
	A0	-0.41±0.63MJ	1.78±1.64MJ
	A1	1.167±0.042m^2	0.962±0.091m^2
	E0	0.283±0.077MJ	0.700±0.075MJ
	E1	0.045±0.005m^2	0.018±0.008m^2
EXTRAPOLATED ANNUAL PERFORMANCE	System efficiency[4]	27% (29%)	27% (30%)
	Estimated annual output[5]	4335MJ (1132MJ/m^2)	4346MJ (1135MJ/m^2)
	Estimated annual electricity consumption[5]	278MJ (73MJ/m^2)	326MJ (85MJ/m^2)
	Estimated annual CO_2 reduction[5]	269kg (70kg/m^2)	260kg (68kg/m^2)



MANUFACTURER	Name	Thermomax Ltd	
	Address	Balloo Crescent Bangor BT19 7UP	
	Telephone	+44 (0) 1247 270411	
	Fax	+44 (0) 1247 270572	
	e-mail	thermomax@aol.com	
SYSTEM	Model name	Solamax	
	Serial number	n/a	
	System type	Evacuated tube	
	Gross area	2.816m^2	
	Aperture area	2.267m^2	
	Absorber area	2.000m^2	
COST	Component cost	n/a	
	Installed cost	n/a	
PERFORMANCE PARAMETERS(1)		Single run off(2)	Split run off(3)
	A0	-0.57±0.62MJ	1.28±1.29MJ
	A1	1.152±0.042m^2	0.927±0.073m^2
	E0	0.301±0.064MJ	0.568±0.083MJ
	E1	0.062±0.004m^2	0.045±0.009m^2
EXTRAPOLATED ANNUAL PERFORMANCE	System efficiency(4)	39% (55%)	38% (54%)
	Estimated annual output(5)	4219MJ (1861MJ/m^2)	4142MJ (1827MJ/m^2)
	Estimated annual electricity consumption(5)	349MJ (154MJ/m^2)	382MJ (169MJ/m^2)
	Estimated annual CO_2 reduction(5)	247kg (109kg/m^2)	235kg (104kg/m^2)



NOTES TO SUMMARY TEST RESULTS

(1)	The performance parameters shown are derived by fitting a straight line to a plot of daily system output against incident radiation. Parameter A0 is the offset of the line and A1 is its slope. Uncertainty bands shown are 95% confidence intervals. E0 and E1 are the corresponding parameters which relate electricity consumption to solar radiation.
(2)	The single run off test schedule consists of a single draw of 150litres of hot water at 6:00pm GMT.
(3)	The split run off test schedule consists of a draw of 60litres of hot water at 7:00am, a further 30litres at 12:00noon and finally 60litres at 5:00pm
(4)	The two tabulated system efficiencies are based on different definitions of collector area. The first is based on Gross area, and the second (in parenthesis) on Absorber area.
(5)	The estimated average performance of the system over a whole year has been derived for collectors on a South facing roof pitched at 30°. 20 year average solar radiation data from Kew, London has been used. To derive the estimated hot water load a cyclic variation of incoming cold water main temperature and a hot water delivery temperature of 55°C have been assumed. The figure below shows how the assumed solar radiation levels and mains water temperature vary by month. The figures have been normalised using collector Aperture area.