ANALYSIS OF PERFORMANCE DATA FROM FOUR ACTIVE SOLAR WATER HEATING INSTALLATIONS

INTERIM REPORT

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Contractor
The Energy Monitoring Company Ltd

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EXECUTIVE SUMMARY

This report describes the analysis of performance data from active solar water heaters at four test sites monitored by the Solar Trade Association. The sites are located at Luton, Croydon, Troon and Tewkesbury. The project set out to monitor the systems for two years, which was considered long enough to give a good picture of performance. The monitoring aimed to provide information on hot water usage and delivery temperature, the energy supplied by the solar collector systems and the proportion of that heat actually used, the useful energy delivered by the solar collector systems and the proportion of the hot water requirement satisfied by the systems, or solar fractions.

Data was gathered from all of the sites throughout 1998 and 1999. The datasets are essentially complete, with only a few weeks data missing from each site. Unfortunately there were a number of problems with the monitoring equipment and with the operation of the solar systems which meant that not all of the data collected could be used to satisfy the objectives outlined above. A failed temperature sensor at Croydon and a problem with the measurement of collector output at Troon meant that results from these two sites could only be produced for only limited parts of the monitoring period. Problems with the operation of the systems at Croydon and Tewkesbury meant that at certain times of year they produced net energy losses. These losses have been ignored in the results presented here. Finally, the system at Tewkesbury appears to have been switched off for the last four months of the trial.

The data provided by the Solar Trade Association has been cleaned, collated and analysed. All of the data has been archived on a compact disk.

The analysis began by examining the hot water consumption of each household. It has been found to be generally lower than expected, and delivery temperatures were also low, with annual averages ranging from 56.4 down to only 43.1°C. The daily consumption pattern varied significantly between the four sites, but water consumption did not vary significantly between the winter and summer months.

The working efficiency of the collectors used in the four systems was then determined, and found to vary between 25 and 48%. The table below summarises the useful energy delivered by each of the systems, and the corresponding solar fractions. Note that for the Tewkesbury site two solar fractions are shown for 1999. The first (shown in brackets) is the fraction of the whole year's hot water energy requirement which was provided by the system. The second figure is the fraction of the hot water energy used during the period for which the system was switched on (January through to August) which was provided by solar.

		Useful solar	Solar fraction
LUTON	1998	3641MJ 1011kWh	55%
	1999	4236MJ 1177kWh	58%
CROYDON	Sep ’98 - May ‘99	1384MJ 384kWh	63%
TROON	1998	2885MJ 801kWh	76%
TEWKESBURY	1998	4063MJ 1129kWh	66%
	1999	3174MJ 882kWh	(48%) 63%

The climate experienced over the monitoring period has been compared with 20 year average values from meteorological stations close to each site. The differences in incident solar radiation are generally small, ranging from –18 to +11%. Using this information the performance of each system has been normalised to give an estimate of the energy output and solar fraction expected in long term operation at each site. The table below shows the results. Again two figures are quoted for the Tewkesbury site during 1999.

		Useful solar	Solar Fraction
LUTON	1998	4038MJ 1122kWh	61%
	1999	4538MJ 1261kWh	62%
CROYDON	Sep ’98 - May ‘99	1821MJ 506kWh	71%
TROON	1998	2898MJ 805kWh	76%
TEWKESBURY	1998	4172MJ 1159kWh	68%
	1999	3334MJ 926kWh	(51%) 67%

In spite of the problems described the project has produced valuable information on the performance of all four systems. It has also produced a series of comprehensive datasets which may be of value in future studies.

CONTENTS

1 INTRODUCTION

This report describes the analysis of performance data from active solar water heaters at four test sites monitored by the Solar Trade Association. The goals of the project included [1]:

- the monitoring of systems for a period long enough to give a good picture of performance, probably two years
- the measurement of hot water usage and delivery temperature
- the measurement of the heat supplied by the solar collector systems
- determination of the proportion of that heat actually used
- calculation of the total useful energy delivered by the solar collector systems over the course of a year
- tabulation of the proportion of the hot water load provided by the solar system, or ‘solar fraction’.

In 1996 the Energy Monitoring Company (EMC) prepared a specification for a package of monitoring equipment which would allow this information to be obtained [1]. EMC installed the first such package at a site in Luton. The remaining three monitoring installations were carried out by the solar system installers.

After data had been collected from Luton for approximately one year some preliminary analysis was carried out by EMC [2]. This revealed one problem with the measurement of solar radiation during the latter part of the year, caused by the sensor becoming detached. However, it served to demonstrate that, when correctly installed, the monitoring system was capable of producing the required information. It also showed the importance of carrying out regular checking of incoming data, in order that problems could be quickly detected and corrected. The Solar Trade Association then collected and collated the information from all four sites over the next two years.

Section 2 of this report summarises the data actually collected from each site. In Sections 3, 4, 5 and 6 the results of analysing data from each of the four sites are presented. Finally, Section 7 summarises the results and conclusions from the project.

2 DATA COLLECTED

As described in the introduction, solar water heaters have been monitored at four sites. These are located at Luton, Croydon, Troon and Tewkesbury. The table below summarises the data which has been produced at each of the sites, in the order in which data collection started.

Site	Data starts	Data finishes
Luton	17/5/1996	11/3/2000
Croydon	1/1/1997	16/3/2000
Troon	10/2/1997	12/3/2000
Tewkesbury	6/10/1997	11/4/2000

Table 2.1: Data collected at each site

As also described in the previous section the aim of the project was to obtain data from each of the four sites over a period of two years. Table 2.1 reveals that if the two year period from January 1998 through to December 1999 is considered then data is available from all sites. This is the period over which the data will be analysed in the remainder of this report.

3 RESULTS FROM THE LUTON SITE

The Luton site was the first to be established, and data has now been collected for a total of almost four years, from May 1996 to March 2000. Figure 3.1 shows the proportion of the data which was successfully collected over the two year analysis period to be considered here.

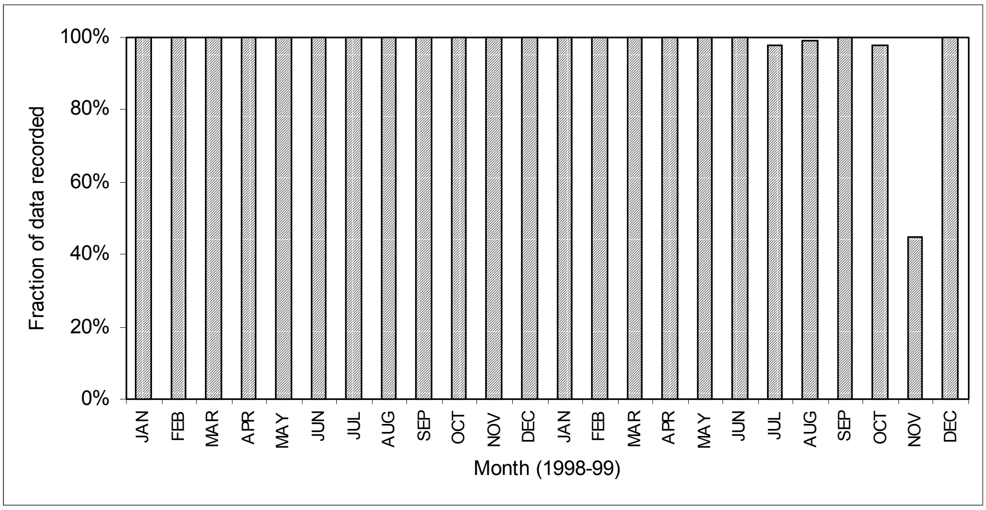


Figure 3.1: Fraction of data collected at Luton

The way in which missing data is handled is described in detail in Appendix B of this report.

Table 3.1 contains the site information which will be used in the analysis and discussion in this section.

Site Location	Luton
Nearest 20 year met station	Cambridge
Collector area	$5m^2$
Collector orientation	South
Collector tilt	30°
Number of occupants	4

Table 3.1: Summary information for Luton Site

3.1 Climate data

Figure 3.2 shows the solar radiation measured on the collectors at Luton, and the average external temperature for each month.

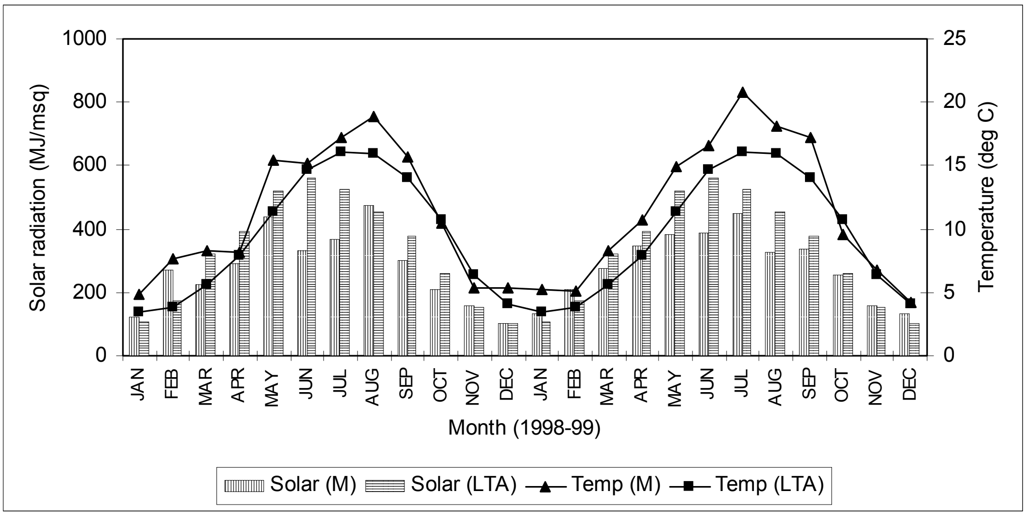


Figure 3.2: Climate data measured at Luton (M) and long term average (LTA) data from Cambridge

Any project such as this which relies on data gathered over a period which is short compared to the life cycle of the systems under investigation is inevitably open to the criticism that the data may not be gathered under realistic conditions. For this reason the 20 year average figures, from the nearest site from which such long term averages are available, Cambridge [3], are also shown on Figure 3.2.

Table 3.2 summarises the data shown on Figure 3.2, giving total radiation values and average temperatures for each of the two years.

Year	Solar Radiation (MJ/m^2)			External Temperature (°C)		
	M	LTA	Diff	M	LTA	Diff
1998	3293	3944	-651 (-17%)	11.1	9.5	1.5
1999	3394		-550 (-14%)	11.4		1.9

Table 3.2: Climate data measured at Luton (M) and long term average (LTA) data from Cambridge

We return to this data in Section 3.5 where it is used to normalise the measured performance of the system to estimate its performance under long term average climate conditions.

3.2 Collector performance

Figure 3.3 shows the solar radiation falling on the collectors at Luton, and the corresponding collector output on an hour by hour basis on 21st June 1998. This day has been chosen because it happened to be a very sunny day at all four of the sites monitored. The incident energy is obtained by taking the measured solar radiation intensity and multiplying it by the collector area from Table 3.1. The energy delivered by the collectors is continuously calculated by the data logger, as described in [1]. Both of these measurements have been totalled over each hour.

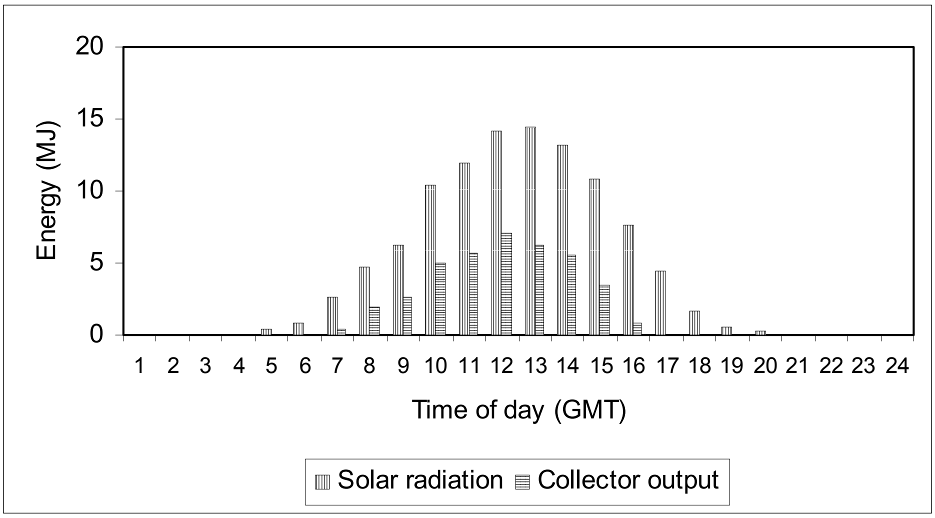


Figure 3.3: Daily profiles of solar radiation and collector output on 21st June 1998

The figure demonstrates a number of features of the operation of the system. Early in the morning, when the radiation level is low, there is insufficient energy landing on the collectors for them to produce any useful output, and they do not switch on. As the incident radiation increases the switch on point is reached and at 7:00am the collectors start to produce a useful output. At this stage the collector efficiency is given by the ratio between the incoming radiation and the output, and is seen to be in region of 50%. Later in the day the radiation level starts to fall, and by 4:00pm the collectors can no longer produce a useful output and switch off. This occurs at a higher radiation level than switch on in the morning because the temperature of the water in the storage tank has risen, and hence higher radiation levels are required for it to be worth operating the system.

The efficiency of the collectors is clearly an important performance parameter, but we have seen that it varies wildly over the course of a day. To obtain an estimate of the performance over the long term, Figure 3.4 shows the energy delivered by the collector panels each month plotted against the energy incident on them.

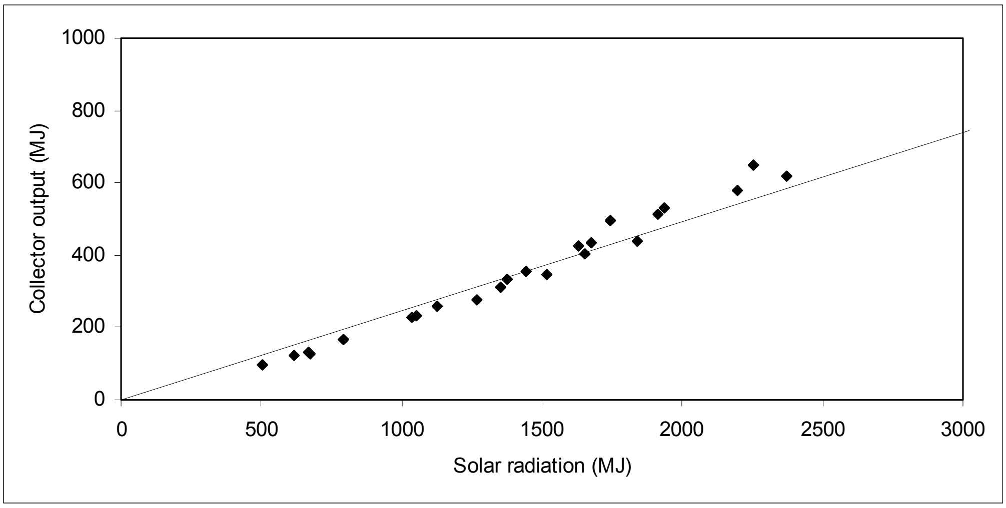


Figure 3.4: Collector output as a function of incident radiation

The slope of the straight line fitted to the points on Figure 3.4 gives a measure of the collector efficiency. It is 25%. The close grouping of the points around the line indicates that this figure is consistent from month to month.

It must be stressed that this is an actual working efficiency. The efficiency figures obtained in this trial cannot be compared directly with the values from laboratory tests. The temperature at which water was supplied to the collectors will obviously have varied significantly over the course of the year. Furthermore, it is highly likely that there will have been periods when the collectors were not able to extract the maximum possible benefit from incident radiation, due to utilisation issues. Indeed the value most appropriate for comparison with laboratory measurements is probably the estimate of 50% obtained from the hourly data shown on Figure 3.3.

3.3 Domestic hot water consumption

The net energy benefit derived from a solar water heating system depends not only on the performance of the associated collector system, but also on the amount of storage provided for that energy and the presence of a consistent requirement for the energy gathered.

Figure 3.5 shows the amount of hot water consumed each month at the Luton site. The graph also shows the average delivery temperature each month, calculated as described in Appendix C of this report.

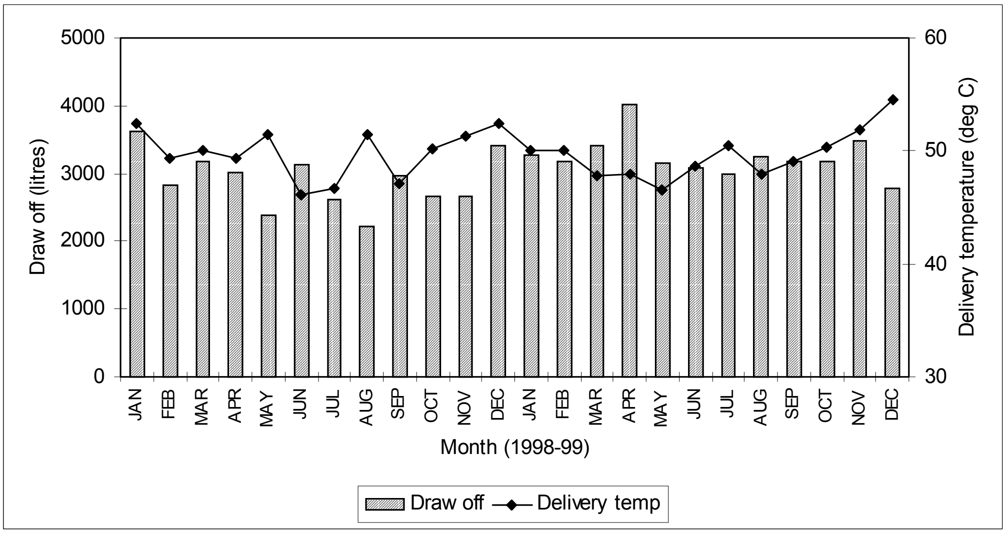


Figure 3.5: Hot water consumption and average delivery temperature

British Gas have suggested that the hot water consumption in a dwelling can be estimated using the formula:

consumption (litres/day) = 38 + 25 × N

where:

N is the number of occupants in the household.

Given that there are reported to be 4 occupants in the Luton house the expected consumption (assuming 30.5 days in each month) is approximately 4200litres/month. It is clear from Figure 3.5 that the measured consumption is consistently lower than this, and Table 3.3 summarises the average hot water consumption over each of the two years.

Year	Average delivery temp (°C)	DHW consumption (litres/month)	Expected consumption (litres/month)	Difference
1998	49.8	2893	4209	-31%
1999	49.6	3248		-23%

Table 3.3: Measured and expected hot water consumption

The volume of water consumed is clearly less than expected from the British Gas formula, and the system manufacturers have since indicated that had they known how low consumption was likely to be they would probably have installed a smaller system. The average domestic hot water supply temperature is also below the commonly assumed value of 60°C. It has a maximum value of around 55°C, and on several occasions falls to almost 45°C.

The next two graphs show how the consumption of hot water is distributed throughout the day. Figure 3.6 covers the winter months, defined here as the period from 1st December through to 31st January.

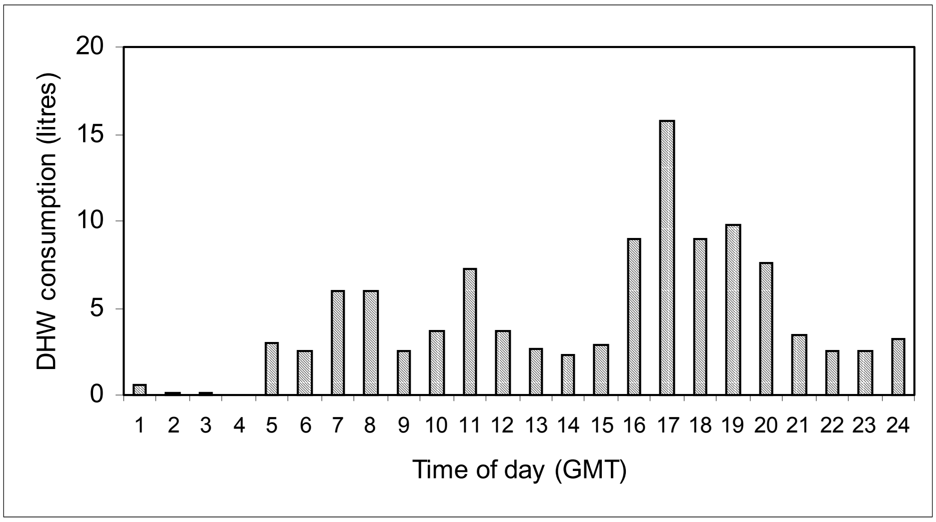


Figure 3.6: Winter hot water consumption profile

Figure 3.7 shows the corresponding hot water consumption profile for the summer months 1st June through to 31st July.

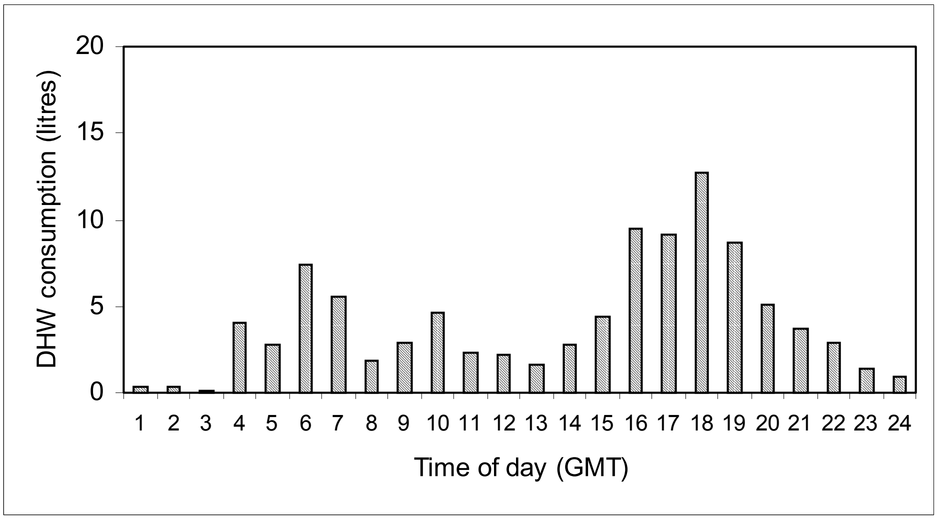


Figure 3.7: Summer hot water consumption profile

The data acquisition systems all run on GMT, and when interpreting Figure 3.7 it is important to remember that BST is one hour ahead of GMT. Applying a simple statistical test to the Winter and Summer profiles indicates that there is no significant change in overall water consumption with season. Both figures show quite clearly that consumption peaks at 5:00 or 6:00pm, an ideal time to make use of solar heated water.

3.4 Evaluating solar contribution and solar fraction

Figure 3.8 shows the monthly contribution from the solar collector, and the estimated energy required for hot water production. As well as the energy which actually comes out of the hot water taps this includes a 15% allowance for system losses. The way in which it is derived is discussed in more detail in Appendix C of this report.

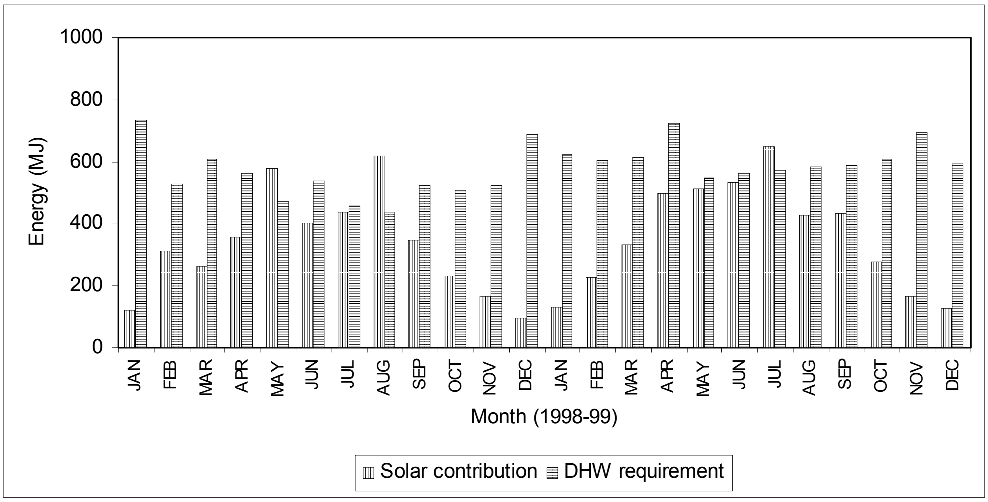


Figure 3.8: Output from collectors and domestic hot water requirement

The total output from the collectors is readily obtained by totalling the monthly outputs shown on Figure 3.8. However, to determine the net benefit from the solar system it is necessary to determine what proportion of the collector output is actually 'useful'. During some months the energy gathered by the solar collectors is greater than the hot water energy actually used. The excess energy is lost from the system - the hot water is stored but never used, and eventually cools due to tank losses. In this situation the excess energy cannot be considered to be of any value, and the delivered energy is simply taken to be the portion of that energy which was actually used. The implications of this assumption are discussed in greater detail in Appendix D of this report. Totalling the resulting useful solar contribution allows the overall energy delivered by the system to be found. Comparing this with the total domestic hot water energy requirement then allows the solar fraction to be determined. Figure 3.9 shows the solar fraction on a month by month basis.

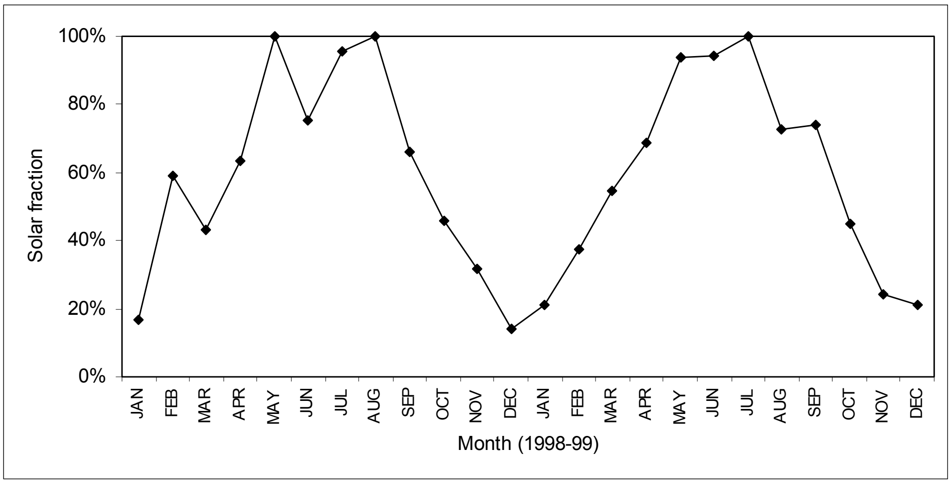


Figure 3.9: Solar fraction

Table 3.4 summarises these results for each of the two years considered.

Year	Solar Collected (MJ)	Useful solar contribution (MJ)	Proportion useful	DHW energy requirement (MJ)	Solar fraction
1998	3930	3641	93%	6570	55%
1999	4311	4236	98%	7311	58%

Table 3.4: Useful solar contribution, hot water energy and solar fraction

3.5 Normalising performance to long term average climate

In Section 3.1 it was noted that the solar radiation received during the monitoring period was approximately 15% less than expected from long term climate recordings.

For relatively small changes in radiation such as these it is reasonable to assume that collector output will vary directly with radiation level, and that the measured collector outputs can therefore be increased by the appropriate amount to give an indication of the output that would have been obtained under more representative conditions. Whilst this will give a reasonable indication of what collector output might have been, it is quite possible that not all of the revised output would have been useful. In particular, if the system was already meeting the entire hot water requirement then increasing the collector output will not provide any extra useful energy. In this situation decreasing the collector output also has no effect on the useful solar contribution, until it is decreased beyond the point where the system no longer satisfies the entire requirement.

In view of these considerations it is necessary first to scale the system output and then to re-evaluate the proportion of that output which is useful. Table 3.5 shows the results of carrying out this normalisation for the Luton site.

Year	Useful solar contribution (MJ)	DHW energy requirement (MJ)	Solar Fraction
1998	4038	6570	61%
1999	4538	7311	62%

Table 3.5: Useful solar contribution, hot water energy and solar fraction (normalised to 20 year average climate)

For this system the normalisation process makes only a small difference to the solar contribution. Figure 3.1 shows that the main discrepancies between measured and long term average climate occur in the summer. Figure 3.8 shows that for this site the solar fraction is close to 100% in the summer. Thus the increase in collector output postulated in the normalisation process is largely not useful, and does not contribute to the overall useful solar contribution.

4 RESULTS FROM THE CROYDON SITE

The Croydon site was the second to be established, in January 1997, and data has now been collected for over three years. Figure 4.1 shows the proportion of the data which was successfully collected over the two year analysis period to be considered here.

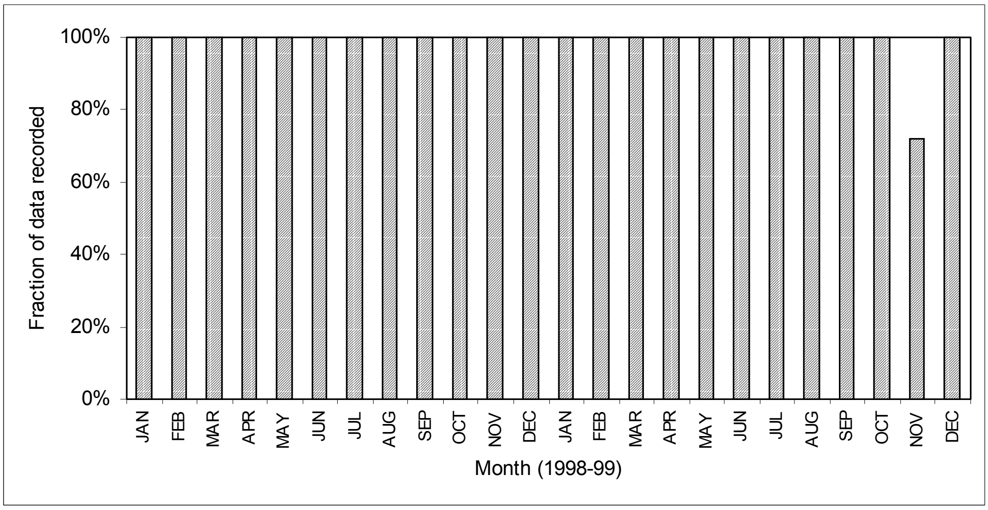


Figure 4.1: Fraction of data collected at Croydon

The way in which missing data is handled is described in detail in Appendix B of this report.

Table 4.1 contains the site information which will be used in the analysis and discussion in this section.

Site Location	Croydon
Nearest 20 year met station	London
Collector area	3m^2
Collector orientation	South
Collector tilt	50°
Number of occupants	2

Table 4.1: Summary information for Croydon Site

4.1 Climate data

Figure 4.2 shows the solar radiation measured on the collectors at Croydon, and the average external temperature for each month.

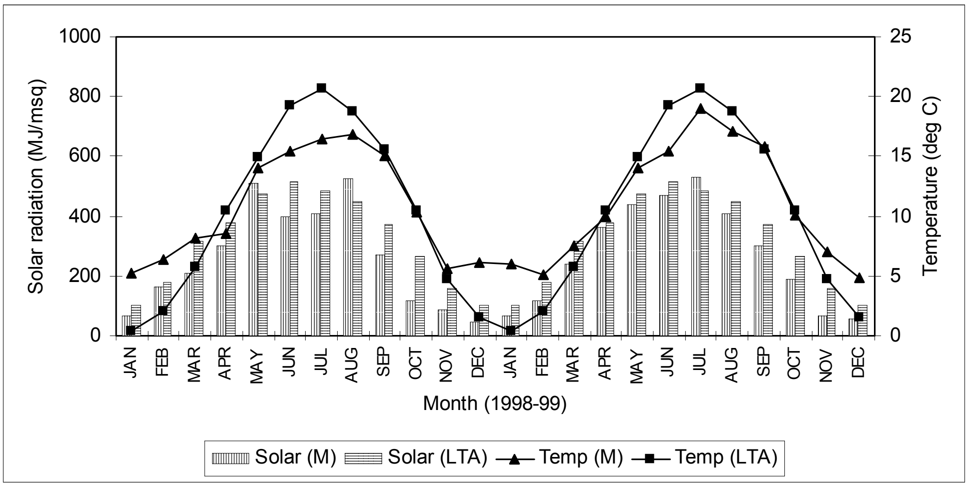


Figure 4.2: Climate data measured at Croydon (M) and long term average (LTA) data from London

Any project such as this which relies on data gathered over a period which is short compared to the life cycle of the systems under investigation is inevitably open to the criticism that the data may not be gathered under realistic conditions. For this reason the 20 year average figures, from the nearest site from which such long term averages are available, London [3], are also shown on Figure 4.2.

Table 4.2 summarises the data shown on Figure 4.2, giving total radiation values and average temperatures for each of the two years.

Year	Solar Radiation (MJ/m^2)			External Temperature (°C)		
	M	LTA	Diff	M	LTA	Diff
1998	3103	3790	-687 (-18%)	10.7	10.4	0.3
1999	3249		-541 (-14%)	11.0		0.6

Table 4.2: Climate data measured at Croydon (M) and long term average (LTA) data from London

We return to this data in Section 4.5 where it is used to normalise the measured performance of the system to estimate its performance under long term average climate conditions.

4.2 Collector performance

Figure 4.3 shows the solar radiation falling on the collectors at Croydon, and the corresponding collector output on an hour by hour basis on 21st June 1998. This day has been chosen because it happened to be a very sunny day at all four of the sites monitored. The incident energy is obtained by taking the measured solar radiation intensity and multiplying it by the collector area from Table 4.1. The energy delivered by the collectors is continuously calculated by the data logger, as described in [1]. Both of these measurements have been totalled over each hour.

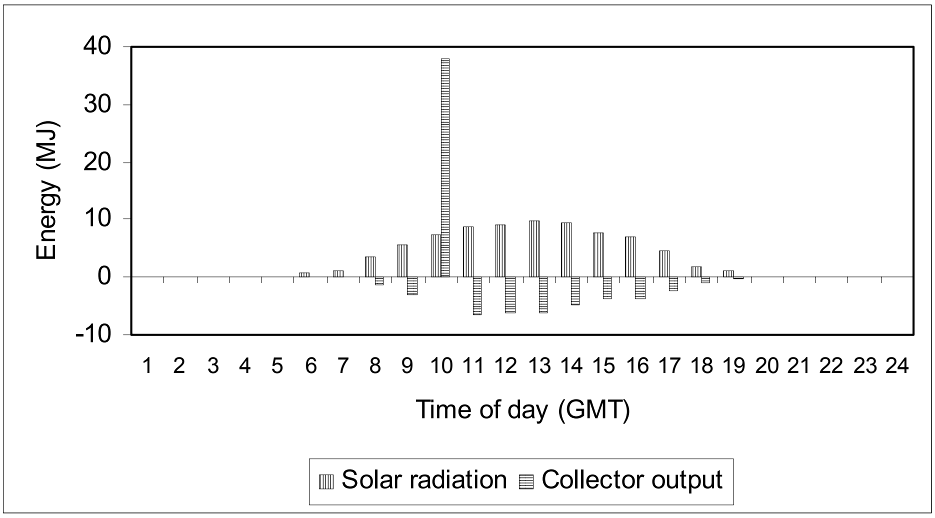


Figure 4.3: Daily profiles of solar radiation and collector output on 21st June 1998

The figure provides the first indication that there are some problems with the data collected at the Croydon site. For most of the day the system appears to lose energy, but during one hour it actually produces an output well in excess of the incident solar radiation. To try to provide further insight into this Figure 4.4 shows the raw temperature data recorded at 15 minute intervals on June 21st 1998.

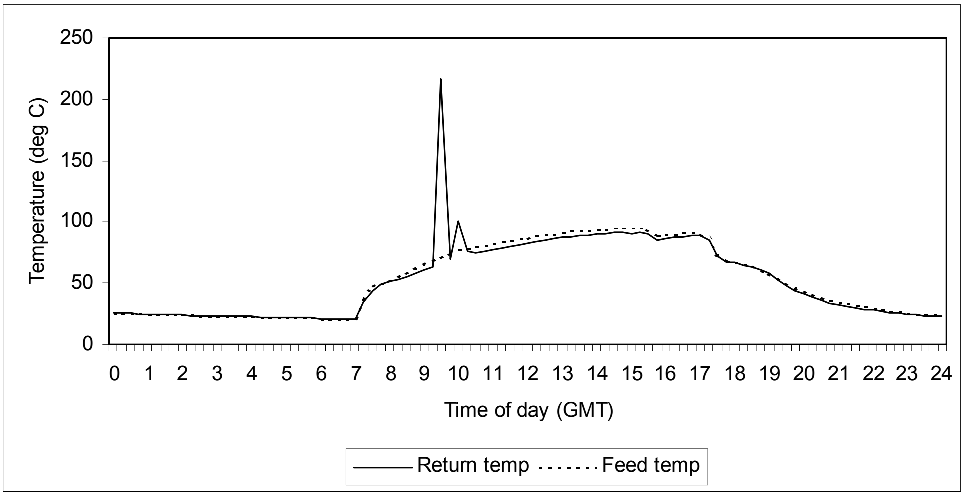


Figure 4.4: Raw temperature data recorded from collectors on June 21st 1998

Figure 4.4 shows quite clearly that for the bulk of the day the temperature of the fluid returning from the collector is slightly lower than the temperature at which working fluid is being supplied to it. This explains the net energy losses calculated by the logger and shown on Figure 4.3. At night, when the system is dormant, the two readings are very close, suggesting that the problem is not one of sensor calibration. At one stage during the day there is an erroneous spike, where the temperature of water returning from the collector appears to peak at over 200°C. This is an unreasonable value, and clearly points to a problem with the monitoring equipment. This explains the very large positive energy output registered by the data logger for the period between 9:00 and 10:00am.

One possible explanation for the consistently negative outputs from the collector is that the two temperature sensors were installed the wrong way round. In this case the data can be ‘corrected’ simply by swapping the two readings and negating the recorded energy output. However, an inspection of the site after this problem was first noted in [2] confirmed that the sensors were in fact correctly installed. Furthermore, the problem is only observed at certain times, and if it was to be explained by swapped sensors this would imply that they had been changed around repeatedly over the course of the monitoring period. It is therefore concluded that this is a problem with the solar system itself, rather than with the monitoring equipment. One possible explanation is a problem with the system controls. Even in the height of summer the recorded collector flow rate never shows a clear plateau, suggesting that the pump never runs continuously. This is in marked contrast to the other installations, where on bright days the flow is constant at its maximum value from early in the morning through to mid afternoon, by which stage the storage tank is presumably fully heated. It may be that the cycling of the pump at Croydon causes hot water to be circulated into the collector pipework where it is then allowed to cool, accounting for the energy losses observed. Without further more detailed data, however, this remains speculation.

Examination of all the data recorded in June indicates that the temperature spiking problem occurs on one other occasion. Examination of the remaining data from this site reveals that the data is reliable between August 1998 and February 1999, but that the problem then returns, and the sensor eventually fails completely in April 1999. In order to maximise the amount of information extracted from the dataset a simple filter was incorporated into the data analysis software to detect these spikes. When a temperature measurement is deemed unreliable the resulting collector output is ignored, and the correct value assumed to be the same as that recorded over the previous 15 minute period.

The efficiency of the collectors is clearly an important performance parameter, but we have seen that it varies wildly over the course of a day. To obtain an estimate of the performance over the long term, Figure 4.5 shows the energy delivered by the collector panels each month plotted against the energy incident on them.

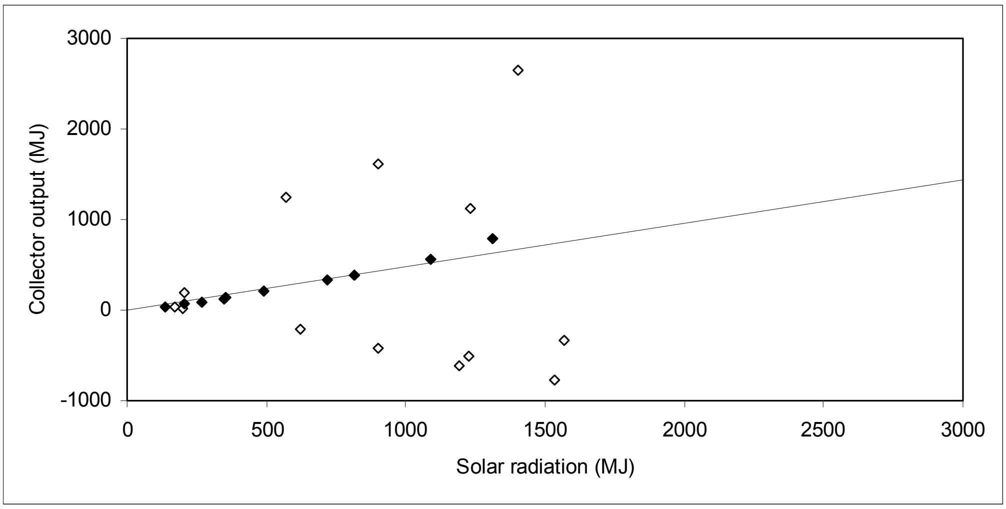


Figure 4.5: Collector output as a function of incident radiation

The figure further confirms that there are major problems with the data. In spite of the filtering of rogue collector temperature data the position of the points towards the top of the plot indicates that for some months the collectors were operating at an apparent efficiency well in excess of 100%. However, a small subset of the monthly energy totals appear to be reasonable, and a straight line has been fitted to these to estimate the system efficiency when it is working correctly. The 10 points used in this calculation are filled on the figure, and the slope of the line fitted to them indicates a collector efficiency of 48%.

It must be stressed that this is an actual working efficiency. The efficiency figures obtained in this trial cannot be compared directly with the values from laboratory tests. The temperature at which water was supplied to the collectors will obviously have varied significantly over the course of the year. Furthermore, it is highly likely that there will have been periods when the collectors were not able to extract the maximum possible benefit from incident radiation, due to utilisation issues.

4.3 Domestic hot water consumption

The net energy benefit derived from a solar water heating system depends not only on the performance of the associated collector system, but also on the amount of storage provided for that energy and the presence of a consistent requirement for the energy gathered.

Figure 4.6 shows the amount of hot water consumed each month at the Croydon site. The graph also shows the average delivery temperature each month, calculated as described in Appendix C of this report.

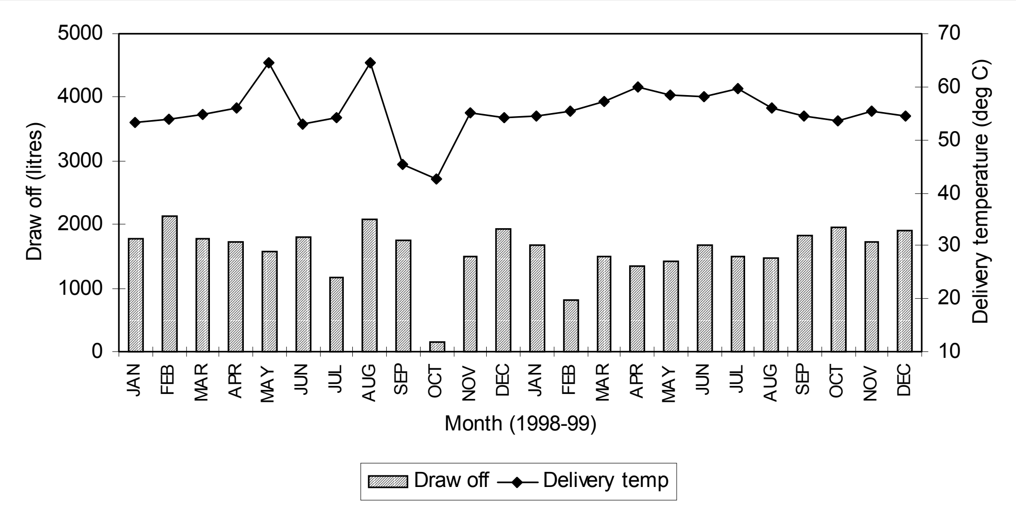


Figure 4.6: Hot water consumption and average delivery temperature

The graph shows that the consumptions recorded in October 1998 and, to a lesser extent, in February 1999 were abnormally low. The most likely reason for this is that the family may have been away for a large part of each month.

British Gas have suggested that the hot water consumption in a dwelling can be estimated using the formula:

$$\text{consumption (litres/day)} = 38 + 25 \times N$$

where:

N is the number of occupants in the household.

Given that there are reported to be 2 occupants in the Croydon house the expected consumption (assuming 30.5 days in each month) is approximately 2680litres/month. It is clear from Figure 4.6 that the measured consumption is consistently lower than this, and Table 4.3 summarises the average hot water consumption over each of the two years.

Year	DHW consumption (litres/month)	Expected consumption (litres/month)	Difference
1998	1615	2684	-40%
1999	1566		-42%

Table 4.3: Measured and expected hot water consumption

The average domestic hot water supply temperature is also slightly below the commonly assumed value of 60°C.

The next two graphs show how the consumption of hot water is distributed throughout the day. Figure 4.7 covers the winter months, defined here as the period from 1st December through to 31st January.

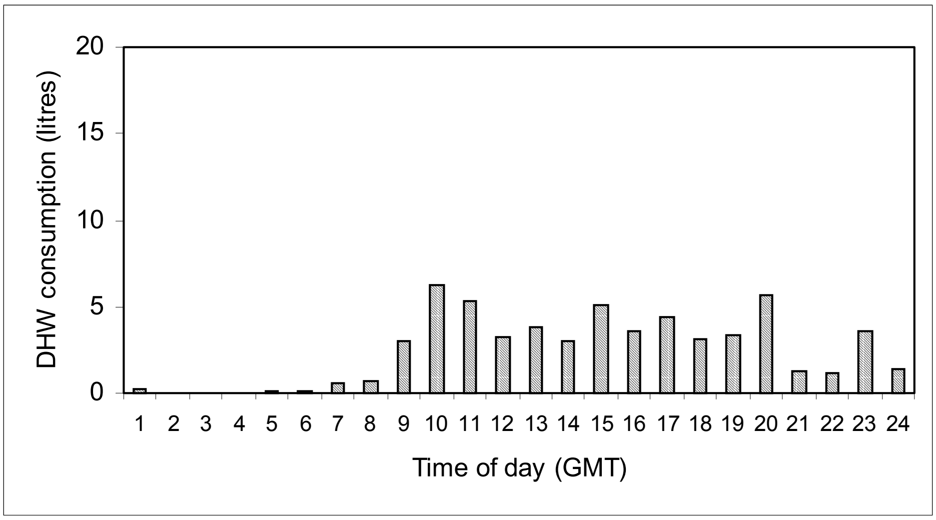


Figure 4.7: Winter hot water consumption profile

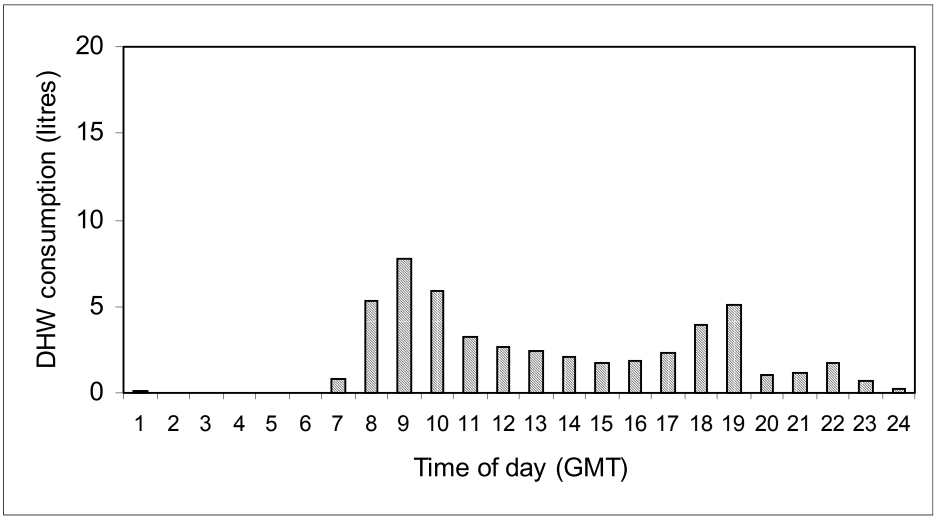


Figure 4.8 shows the corresponding hot water consumption profile for the summer months 1st June through to 31st July.

Figure 4.8: Summer hot water consumption profile

The data acquisition systems all run on GMT, and when interpreting Figure 4.8 it is important to remember that BST is one hour ahead of GMT. Applying a simple statistical test to the Winter and Summer profiles indicates that there is no significant change in overall water consumption with season. The figures indicate that consumption peaks in the morning, not an ideal scenario for making use of solar heated water.

4.4 Evaluating solar contribution and solar fraction

Figure 4.9 shows the monthly contribution from the solar collector, and the estimated energy required for hot water production. As well as the energy which actually comes out of the hot water taps this includes a 15% allowance for system losses. The way in which it is derived is discussed in more detail in Appendix C of this report.

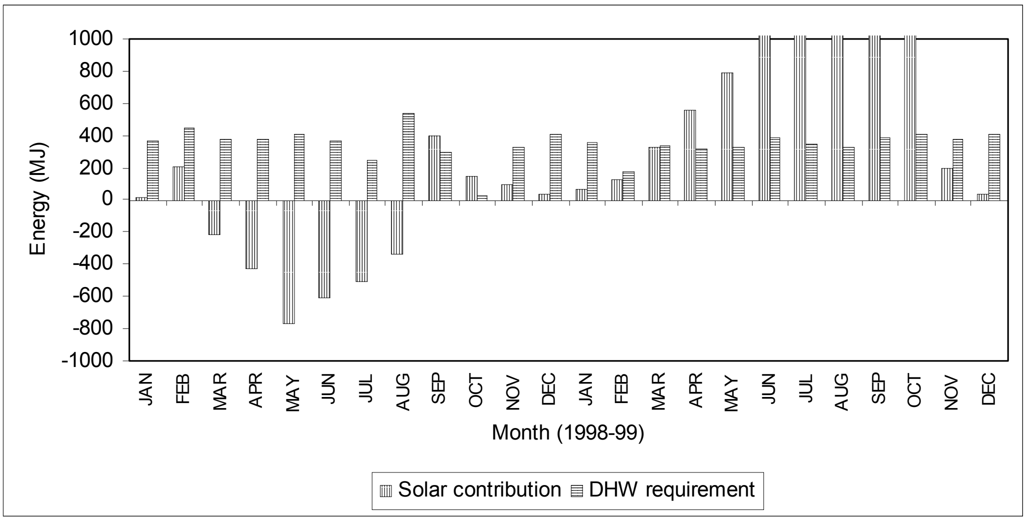


Figure 4.9: Output from collectors and domestic hot water requirement
The figure again reveals the problems with the monitoring at this site. In particular the progressive failure of the collector temperature sensor makes it impossible to infer the amount of energy gathered after May 1999. The second problem with the data is the large negative solar contributions which are observed from March to August 1998.

Figure 4.10 shows the collector output and domestic hot water energy requirement over the period from September 1998 through to May 1999, when neither of these problems was manifesting itself.

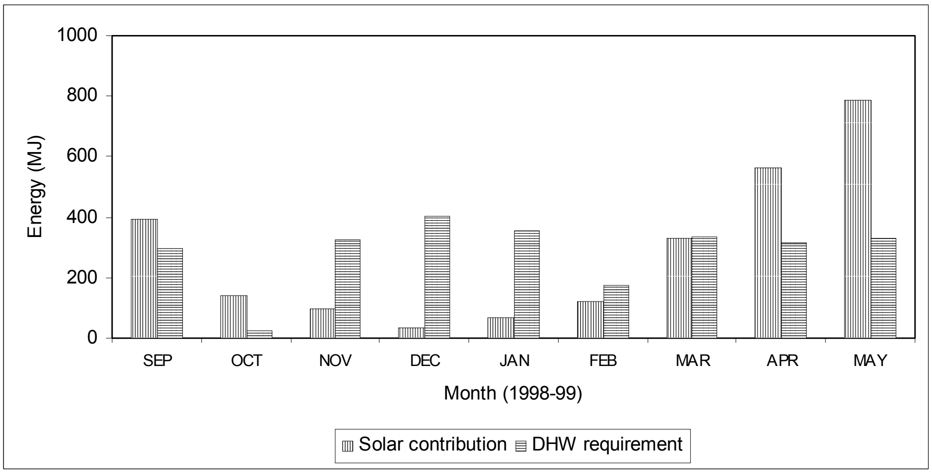


Figure 4.10: Collector output and domestic hot water requirement

As described in Section 4.3, the household had an extremely low water consumption. To make matters even worse the two months with abnormally low loads, October 1998 and February 1999, are both included in the analysis period. Figure 4.10 confirms that in October a significant amount of the energy delivered by the collectors was wasted because the water consumption was so low.

The total output from the collectors over this period is readily obtained by totalling the monthly outputs shown on Figure 4.10. However, to determine the net benefit from the solar system it is necessary to determine what proportion of the collector output is actually 'useful'. During some months the energy gathered by the solar collectors is greater than the hot water energy actually used. The excess energy is lost from the system - the hot water is stored but never used, and eventually cools due to tank losses. In this situation the excess energy cannot be considered to be of any value, and the delivered energy is simply taken to be the portion of that energy which was actually used. The implications of this assumption are discussed in greater detail in Appendix D of this report. Totalling the resulting useful solar contribution allows the overall energy delivered by the system to be found. Comparing this with the total domestic hot water energy requirement then allows the solar fraction to be determined. Figure 4.11 shows the solar fraction on a month by month basis.

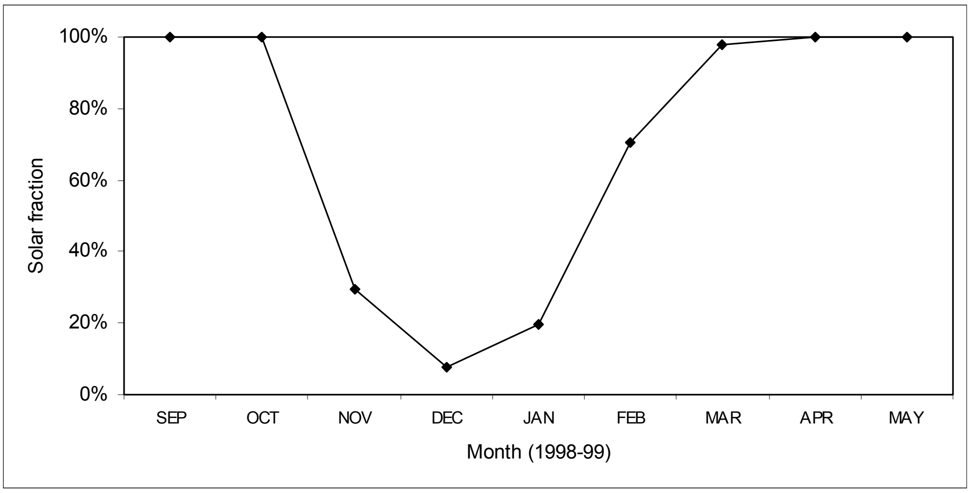


Figure 4.11: Solar fraction

Table 4.4 summarises these results for the period analysed.

Period	Solar collected (MJ)	Useful solar contribution (MJ)	Proportion useful	DHW energy requirement (MJ)	Solar Fraction
Sept 1998 to May 1999	2532	1613	64%	2555	63%

Table 4.4: Useful solar contribution, hot water energy and solar fraction

The table reflects the fact that the very low water consumption in this house significantly hampered the performance of the solar system: only 64% of the energy gathered was actually used.

When interpreting the results shown it must be remembered that they do not include data from a complete year. In fact the solar radiation falling on the collectors over the period analysed was less than half of that expected over an average whole year. There were two reasons for this. Most obviously, the period does not include the summer months. However, the months which are included were significantly duller than would be expected on average, with the total radiation being 25% less than the average figure.

It is not feasible to normalise the results to obtain a result for the whole year, for the simple reason that although the output of the collectors could be predicted with reasonable certainty it would be impossible to predict how effectively that energy would be used, and hence the useful solar output cannot be determined. However, it is possible to estimate the impact of the deviation from long term average climate, and Section 4.5 addresses this issue.

4.5 Normalising performance to long term average climate

It has been noted that the solar radiation received during the period analysed was 25% less than expected from long term climate recordings.

For relatively small changes in radiation such as these it is reasonable to assume that collector output will vary directly with radiation level, and that the measured collector outputs can therefore be increased by the appropriate amount to give an indication of the output that would have been obtained under more representative conditions. Whilst this will give a reasonable indication of what collector output might have been, it is quite possible that not all of the revised output would have been useful. In particular, if the system was already meeting the entire hot water requirement then increasing the collector output will not provide any extra useful energy. In this situation decreasing the collector output also has no effect on the useful solar contribution, until it is decreased beyond the point where the system no longer satisfies the entire requirement.

In view of these considerations it is necessary first to scale the system output and then to re-evaluate the proportion of that output which is useful. Table 4.5 shows the results of carrying out this normalisation for the Croydon site.

Period	Useful solar contribution (MJ)	DHW energy requirement (MJ)	Solar Fraction
September 1998 to May 1999	1821	2555	71%

Table 4.5: Useful solar contribution, hot water energy and solar fraction (normalised to 20 year average climate)

5 RESULTS FROM THE TROON SITE

Data collection at the Troon site began in February 1997, and three years data has now been gathered. Figure 5.1 shows the proportion of the data which was successfully collected over the two year analysis period to be considered here.

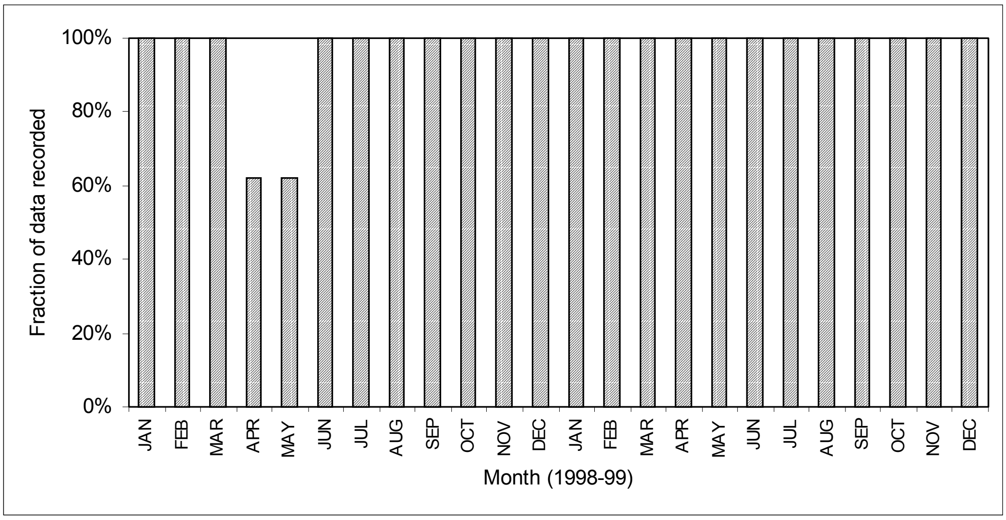


Figure 5.1: Fraction of data collected at Troon

The way in which missing data is handled is described in detail in Appendix B of this report.

Table 5.1 contains the site information which will be used in the analysis and discussion in this section.

Site Location	Troon
Nearest 20 year met station	Glasgow
Collector area	$4m^2$
Collector orientation	210° E of N
Collector tilt	30°
Number of occupants	4

Table 5.1: Summary information for Troon Site

5.1 Climate data

Figure 5.2 shows the solar radiation measured on the collectors at Troon, and the average external temperature for each month.

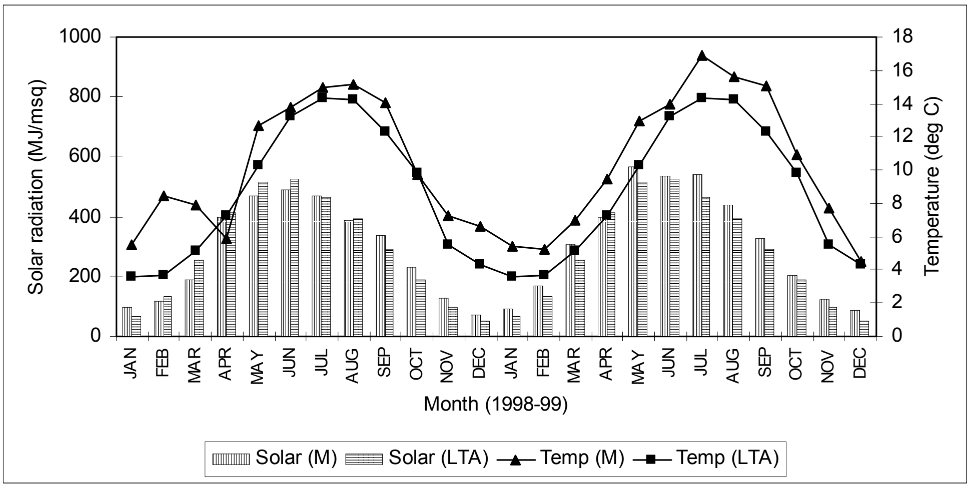


Figure 5.2: Climate data measured at Troon (M) and long term average (LTA) data from Glasgow

Any project such as this which relies on data gathered over a period which is short compared to the life cycle of the systems under investigation is inevitably open to the criticism that the data may not be gathered under realistic conditions. For this reason the 20 year average figures, from the nearest site from which such long term averages are available, Glasgow [3], are also shown on Figure 5.2.

Table 5.2 summarises the data shown on Figure 5.2, giving total radiation values and average temperatures for each of the two years.

Year	Solar Radiation (MJ/m^2)			External Temperature (°C)		
	M	LTA	Diff	M	LTA	Diff
1998	3377	3400	-22 (-1%)	10.2	8.6	1.4
1999	3786		+386 (11%)	10.4		1.8

Table 5.2: Climate data measured at Troon (M) and long term average (LTA) data from Glasgow

We return to this data in Section 5.5 where it is used to normalise the measured performance of the system to estimate its performance under long term average climate conditions.

5.2 Collector performance

Figure 5.3 shows the solar radiation falling on the collectors at Troon, and the corresponding collector output on an hour by hour basis on 21st June 1998. This day has been chosen because it happened to be a very sunny day at all four of the sites monitored. The incident energy is obtained by taking the measured solar radiation intensity and multiplying it by the collector area from Table 5.1. The energy delivered by the collectors is continuously calculated by the data logger, as described in [1]. Both of these measurements have been totalled over each hour.

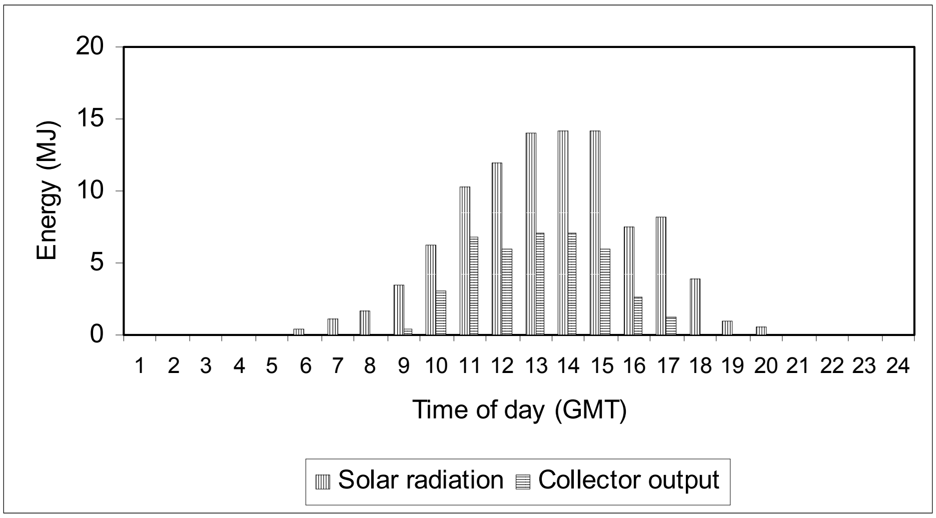


Figure 5.3: Daily profiles of solar radiation and collector output on 21st June 1998

The figure demonstrates a number of features of the operation of the system. Early in the morning, when the radiation level is low, there is insufficient energy landing on the collectors for them to produce any useful output, and they do not switch on. As the incident radiation increases the switch on point is reached and at 10:00am the collectors start to produce a useful output. At this stage the collector efficiency is given by the ratio between the incoming radiation and the output, which peaks at 66% and then continues at 50% for the next few hours. Later in the day the radiation level starts to fall, and by 5:00pm the collectors can no longer produce a useful output and switch off. This occurs at a higher radiation level than switch on in the morning because the temperature of the water in the storage tank has risen, and hence higher radiation levels are required for it to be worth operating the system.

The efficiency of the collectors is clearly an important performance parameter, but we have seen that it varies wildly over the course of a day. To obtain an estimate of the performance over the long term, Figure 5.4 shows the energy delivered by the collector panels each month plotted against the energy incident on them.

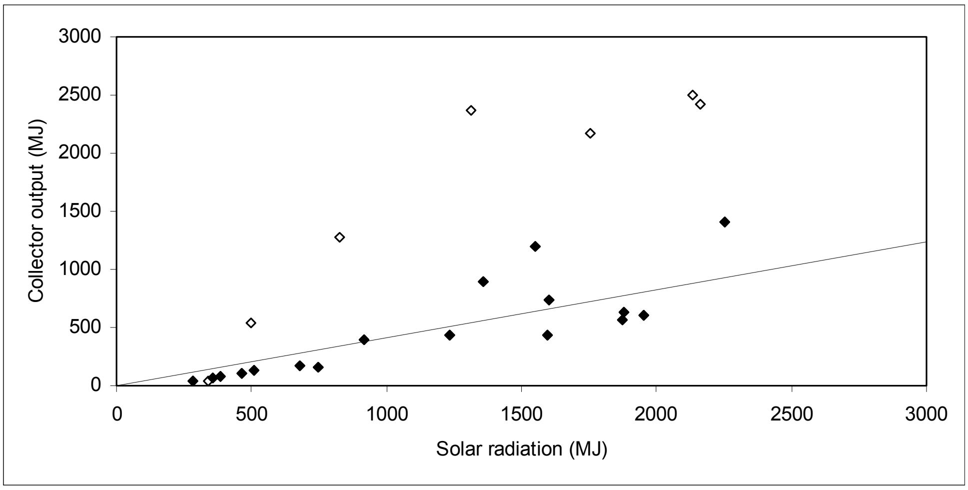


Figure 5.4: Collector output as a function of incident radiation

The figure indicates that are some problems with the data from Troon. The points towards the top of the plot indicate that for some months the collectors were operating at an apparent efficiency in excess of 100%. However, the remaining monthly energy totals appear to be reasonable, and a straight line has been fitted to these to estimate the system efficiency when it is working correctly. The 17 points used in this calculation are filled on the figure, and the slope of the line fitted to them indicates a collector efficiency of 41%. The rather large scatter of these points about the fitted line indicates that the efficiency is not consistent from month to month.

It must be stressed that this is an actual working efficiency. The efficiency figures obtained in this trial cannot be compared directly with the values from laboratory tests. The temperature at which water was supplied to the collectors will obviously have varied significantly over the course of the year. Furthermore, it is highly likely that there will have been periods when the collectors were not able to extract the maximum possible benefit from incident radiation, due to utilisation issues. Indeed the value most appropriate for comparison with laboratory measurements is probably the estimate of 50 to 60% obtained from the hourly data shown on Figure 5.3.

5.3 Domestic hot water consumption

The net energy benefit derived from a solar water heating system depends not only on the performance of the associated collector system, but also on the amount of storage provided for that energy and the presence of a consistent requirement for the energy gathered.

Figure 5.5 shows the amount of hot water consumed each month at the Troon site. The graph also shows the average delivery temperature each month, calculated as described in Appendix C of this report.

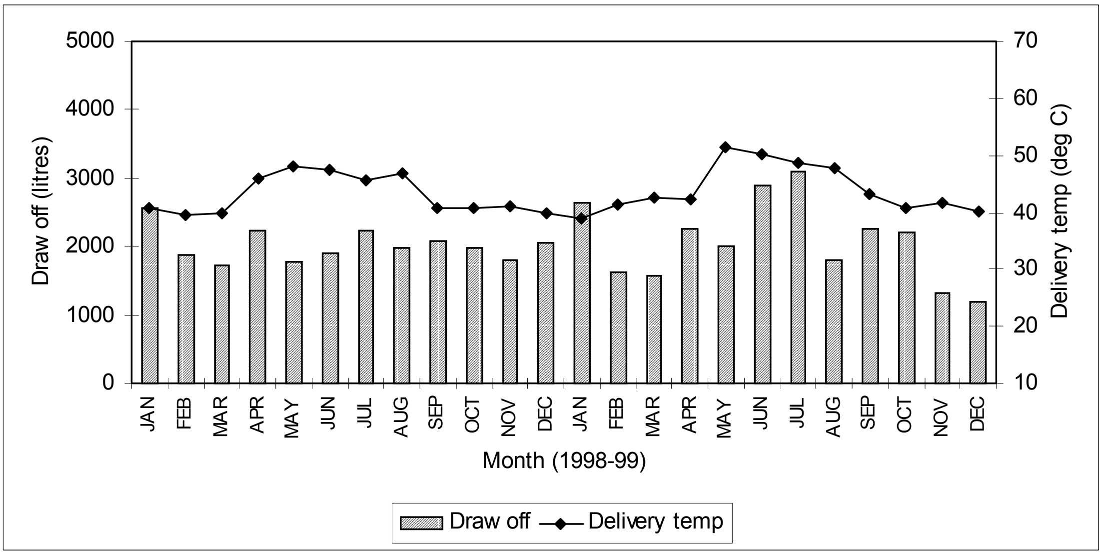


Figure 5.5: Hot water consumption and average delivery temperature

British Gas have suggested that the hot water consumption in a dwelling can be estimated using the formula:

consumption (litres/day) = 38 + 25 × N

where:

N is the number of occupants in the household.

Given that there are reported to be 4 occupants in the Troon house the expected consumption (assuming 30.5 days in each month) is approximately 4200litres/month. It is clear from Figure 5.5 that the measured consumption is considerably lower than this, and Table 5.3 summarises the average hot water consumption over each of the two years.

Year	DHW consumption (litres/month)	Expected consumption (litres/month)	Difference
1998	2023	4209	-52%
1999	2072		-51%

Table 5.3: Measured and expected hot water consumption

The average domestic hot water supply temperature is also below the commonly assumed value of 60°C. It has a maximum value of around 55°C, and on several occasions falls to almost 45°C.

The next two graphs show how the consumption of hot water is distributed throughout the day. Figure 5.6 covers the winter months, defined here as the period from 1st December through to 31st January.

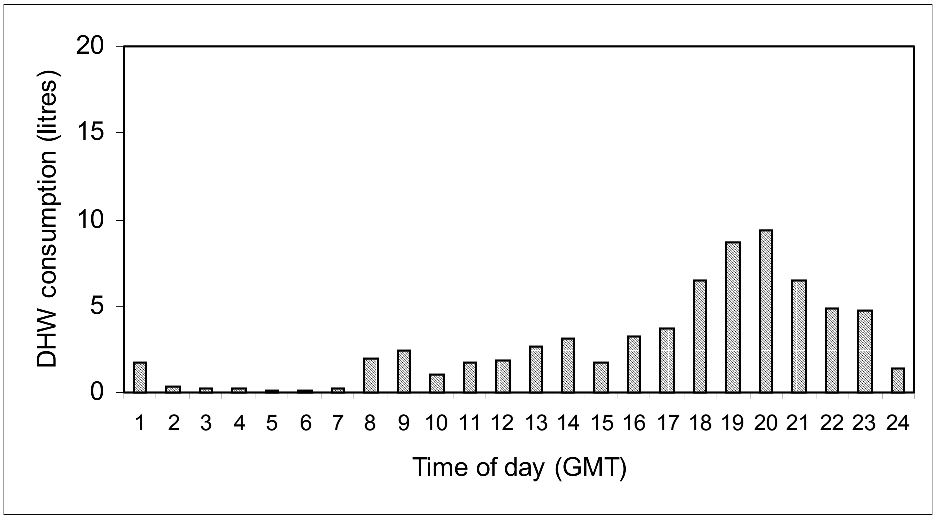


Figure 5.6: Winter hot water consumption profile

Figure 5.7 shows the corresponding hot water consumption profile for the summer months 1st June through to 31st July.

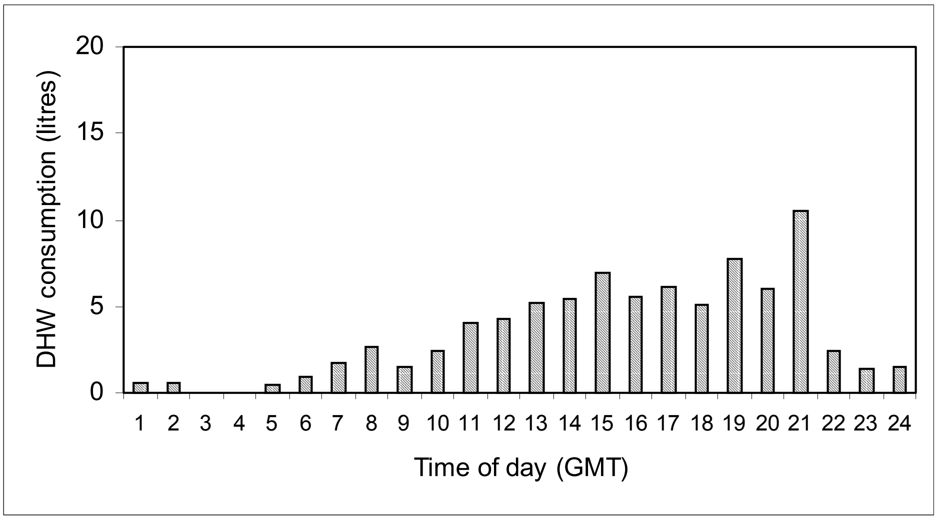


Figure 5.7: Summer hot water consumption profile

The data acquisition systems all run on GMT, and when interpreting Figure 5.7 it is important to remember that BST is one hour ahead of GMT. Applying a simple statistical test to the Winter and Summer profiles indicates that there is no significant change in overall water consumption with season. Both figures show quite clearly that consumption peaks at 8:00 or 9:00pm, a good time to make use of solar heated water.

5.4 Evaluating solar contribution and solar fraction

Figure 5.8 shows the monthly contribution from the solar collector, and the estimated energy required for hot water production. As well as the energy which actually comes out of the hot water taps this includes a 15% allowance for system losses. The way in which it is derived is discussed in more detail in Appendix C of this report.

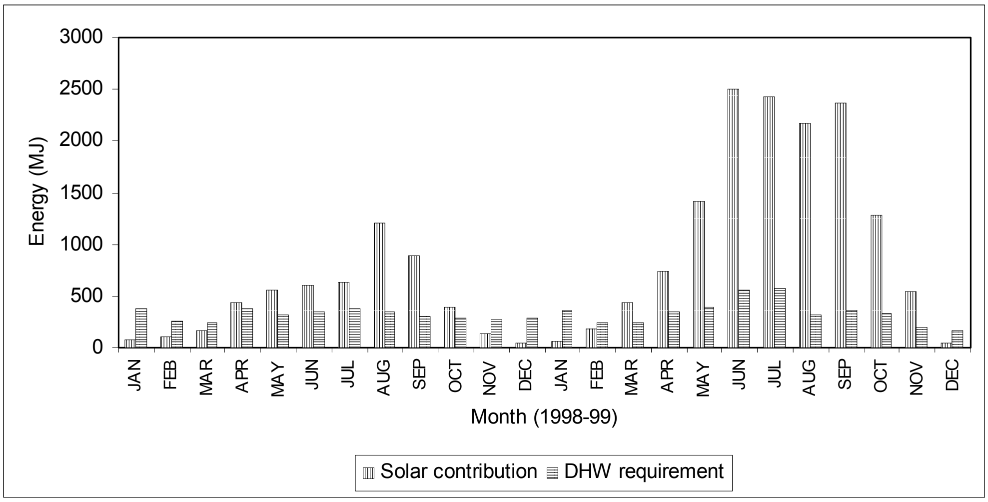


Figure 5.8: Output from collectors and domestic hot water requirement

The total output from the collectors is readily obtained by totalling the monthly outputs shown on Figure 5.8. However, to determine the net benefit from the solar system it is necessary to determine what proportion of the collector output is actually ‘useful’. During some months the energy gathered by the solar collectors is greater than the hot water energy actually used. The excess energy is lost from the system - the hot water is stored but never used, and eventually cools due to tank losses. In this situation the excess energy cannot be considered to be of any value, and the delivered energy is simply taken to be the portion of that energy which was actually used. The implications of this assumption are discussed in greater detail in Appendix D of this report. Totalling the resulting useful solar contribution allows the overall energy delivered by the system to be found. Comparing this with the total domestic hot water energy requirement then allows the solar fraction to be determined. Figure 5.9 shows the solar fraction on a month by month basis. Once again, only data from the first year of monitoring is presented.

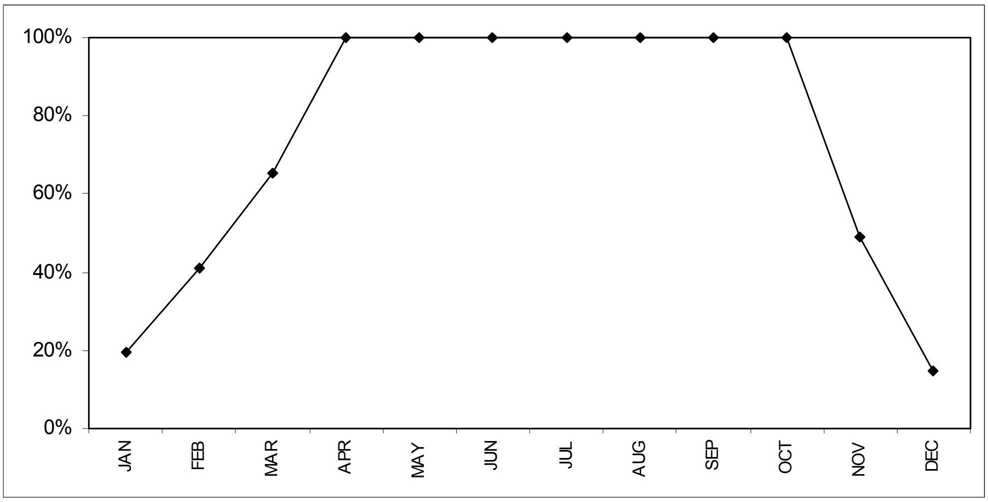


Figure 5.9: Solar fraction

Table 5.4 summarises these results for the first monitoring year.

Year	Solar Collected (MJ)	Useful solar contribution (MJ)	Proportion useful	DHW energy requirement (MJ)	Solar fraction
1998	5255	2884	55%	3813	76%

Table 5.4: Useful solar contribution, hot water energy and solar fraction

5.5 Normalising performance to long term average climate

In Section 5.1 it was noted that the solar radiation received during the monitoring period was approximately 5% more than expected from long term climate recordings.

For relatively small changes in radiation such as these it is reasonable to assume that collector output will vary directly with radiation level, and that the measured collector outputs can therefore be increased by the appropriate amount to give an indication of the output that would have been obtained under more representative conditions. Whilst this will give a reasonable indication of what collector output might have been, it is quite possible that not all of the revised output would have been useful. In particular, if the system was already meeting the entire hot water requirement then increasing the collector output will not provide any extra useful energy. In this situation decreasing the collector output also has no effect on the useful solar contribution, until it is decreased beyond the point where the system no longer satisfies the entire requirement.

In view of these considerations it is necessary first to scale the system output and then to re-evaluate the proportion of that output which is useful. Table 5.5 shows the results of carrying out this normalisation for the Troon site.

Year	Useful solar contribution (MJ)	DHW energy requirement (MJ)	Solar Fraction
1998	2898	3813	76%

Table 5.5: Useful solar contribution, hot water energy and solar fraction (normalised to 20 year average climate)

For this system the normalisation process makes only a small difference to the solar contribution, because the variations between measured and expected radiation levels are themselves small.

6 RESULTS FROM THE TEWKESBURY SITE

The Tewkesbury site was the last to be established. Data collection began in October 1997, and approximately 2½ years data has now been collected. Figure 6.1 shows the proportion of the data which was successfully collected over the two year analysis period to be considered here.

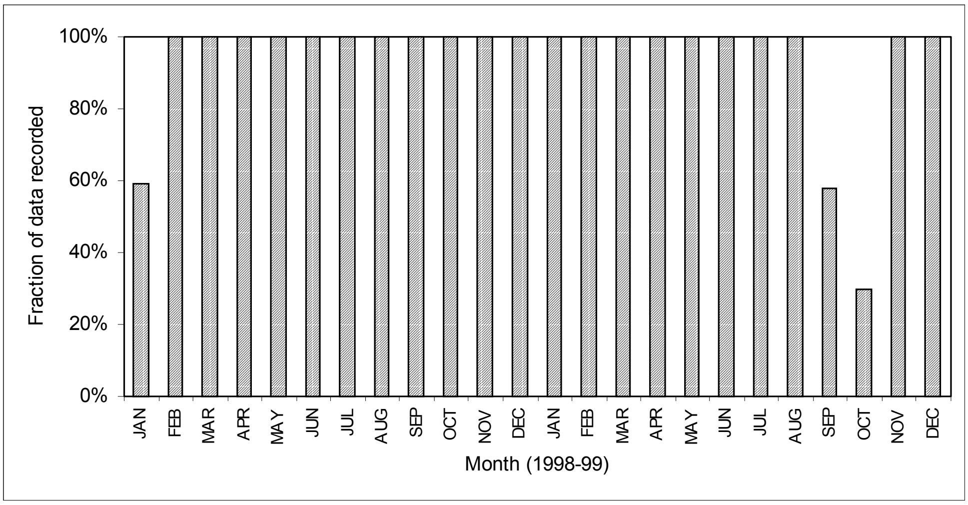


Figure 6.1: Fraction of data collected at Tewkesbury

The way in which missing data is handled is described in detail in Appendix B of this report.

Table 6.1 contains the site information which will be used in the analysis and discussion in this section.

Site Location	Tewkesbury
Nearest 20 year met station	Birmingham
Collector area	$4m^2$
Collector orientation	220° E of N
Collector tilt	30°
Number of occupants	4 to 5

Table 6.1: Summary information for Tewkesbury Site

6.1 Climate data

Figure 6.2 shows the solar radiation measured on the collectors at Tewkesbury, and the average external temperature for each month.

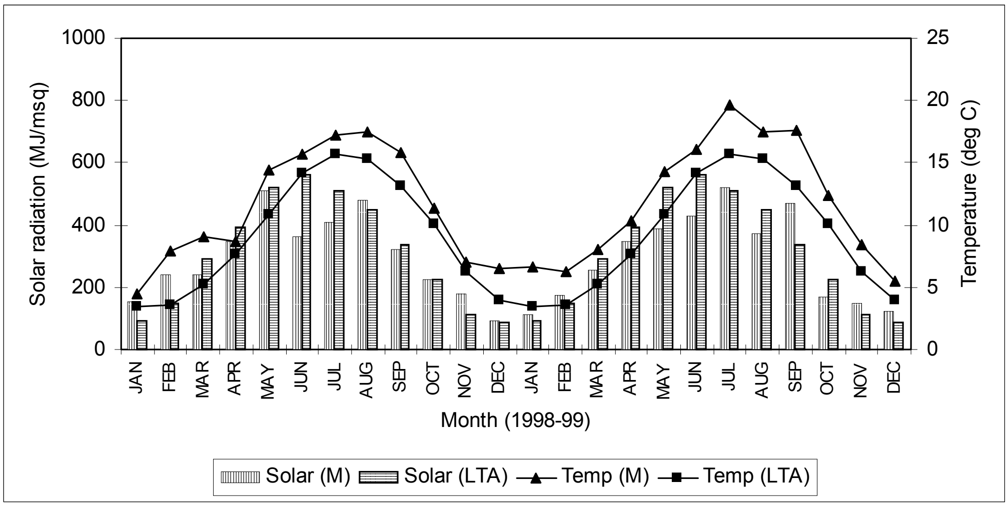


Figure 6.2: Climate data measured at Tewkesbury (M) and long term average (LTA) data from Birmingham

Any project such as this which relies on data gathered over a period which is short compared to the life cycle of the systems under investigation is inevitably open to the criticism that the data may not be gathered under realistic conditions. For this reason the 20 year average figures, from the nearest site from which such long term averages are available, Birmingham [3], are also shown on Figure 6.2.

Table 6.2 summarises the data shown on Figure 6.2, giving total radiation values and average temperatures for each of the two years.

Year	Solar Radiation (MJ/m^2)			External Temperature (°C)		
	M	LTA	Diff	M	LTA	Diff
1998	3545	3723	-178 (-5%)	11.3	9.1	2.2
1999	3498		-225 (-6%)	11.9		2.8

Table 6.2: Climate data measured at Tewkesbury (M) and long term average (LTA) data from Birmingham

We return to this data in Section 6.5 where it is used to normalise the measured performance of the system to estimate its performance under long term average climate conditions.

6.2 Collector performance

Figure 6.3 shows the solar radiation falling on the collectors at Tewkesbury, and the corresponding collector output on an hour by hour basis on 21st June 1998. This day has been chosen because it happened to be a very sunny day at all four of the sites monitored. The incident energy is obtained by taking the measured solar radiation intensity and multiplying it by the collector area from Table 6.1. The energy delivered by the collectors is continuously calculated by the data logger, as described in [1]. Both of these measurements have been totalled over each hour.

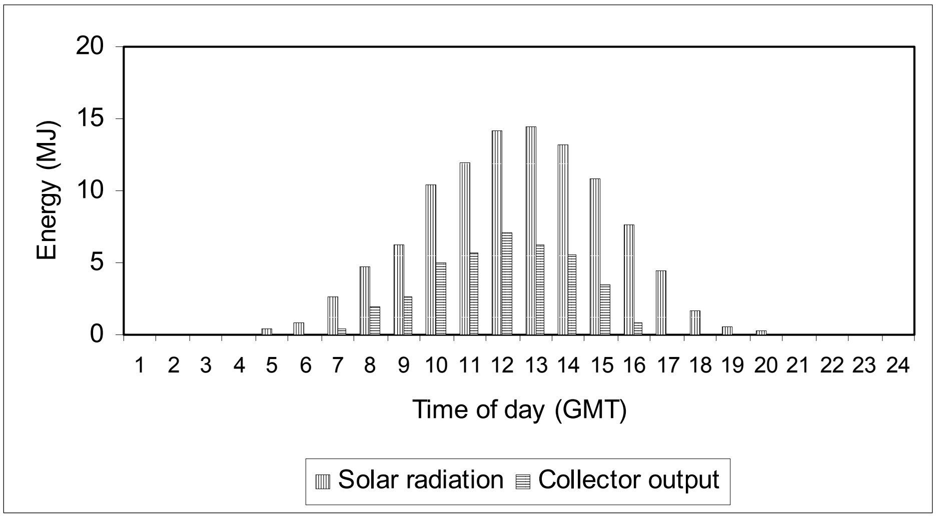


Figure 6.3: Daily profiles of solar radiation and collector output on 21st June 1998

The figure demonstrates a number of features of the operation of the system. Early in the morning, when the radiation level is low, there is insufficient energy landing on the collectors for them to produce any useful output, and they do not switch on. As the incident radiation increases the switch on point is reached and at 8:00am the collectors start to produce a useful output. At this stage the collector efficiency is given by the ratio between the incoming radiation and the output, and is seen to be between 50 and 60%. Later in the day the radiation level starts to fall, and by 4:00pm the collectors can no longer produce a useful output and switch off. This occurs at a higher radiation level than switch on in the morning because the temperature of the water in the storage tank has risen, and hence higher radiation levels are required for it to be worth operating the system.

The efficiency of the collectors is clearly an important performance parameter, but we have seen that it varies wildly over the course of a day. To obtain an estimate of the performance over the long term, Figure 6.4 shows the energy delivered by the collector panels each month plotted against the energy incident on them.

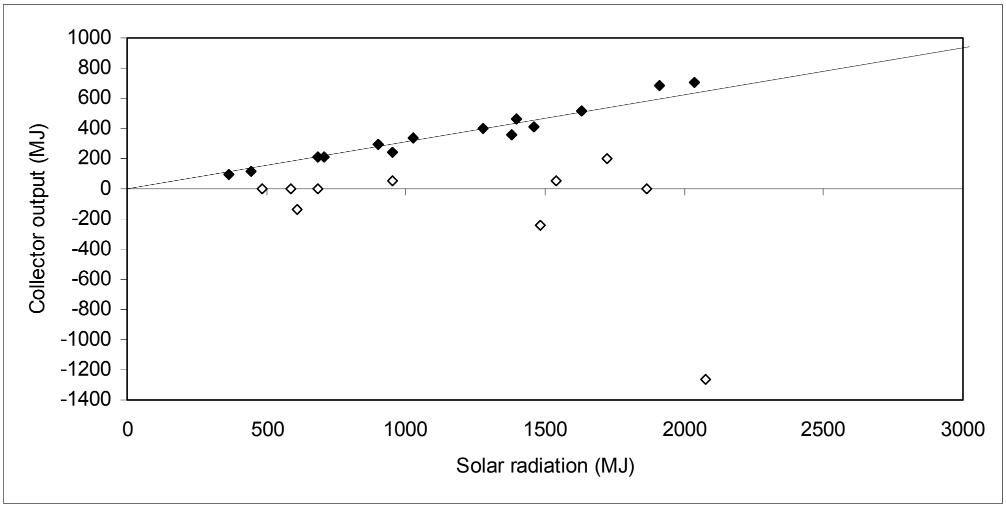


Figure 6.4: Collector output as a function of incident radiation

The plot indicates a number of problems with the data. There are three months in which the collector output is extremely low. For a further four months the output of the collector system was zero. Examination of the recordings of flow through the collectors for these months indicates that it too was zero, suggesting that the collector pump did not run over this period, possibly due to the system being switched off. Finally, there are three months in which the collector output was actually negative, implying that it was a net loser of energy.

The remaining points have been selected, and a straight line fitted to them. The slope of this line gives a measure of the collector efficiency over the times when it was operating 'normally'. It is 31%. The close grouping of the points around the line indicates that, during normal operation, this figure is consistent from month to month.

It must be stressed that this is an actual working efficiency. The efficiency figures obtained in this trial cannot be compared directly with the values from laboratory tests. The temperature at which water was supplied to the collectors will obviously have varied significantly over the course of the year. Furthermore, it is highly likely that there will have been periods when the collectors were not able to extract the maximum possible benefit from incident radiation, due to utilisation issues. Indeed the value most appropriate for comparison with laboratory measurements is probably the estimate of 50 to 60% obtained from the hourly data shown on Figure 6.3.

6.3 Domestic hot water consumption

The net energy benefit derived from a solar water heating system depends not only on the performance of the associated collector system, but also on the amount of storage provided for that energy and the presence of a consistent requirement for the energy gathered.

Figure 6.5 shows the amount of hot water consumed each month at the Tewkesbury site. The graph also shows the average delivery temperature each month, calculated as described in Appendix C of this report.

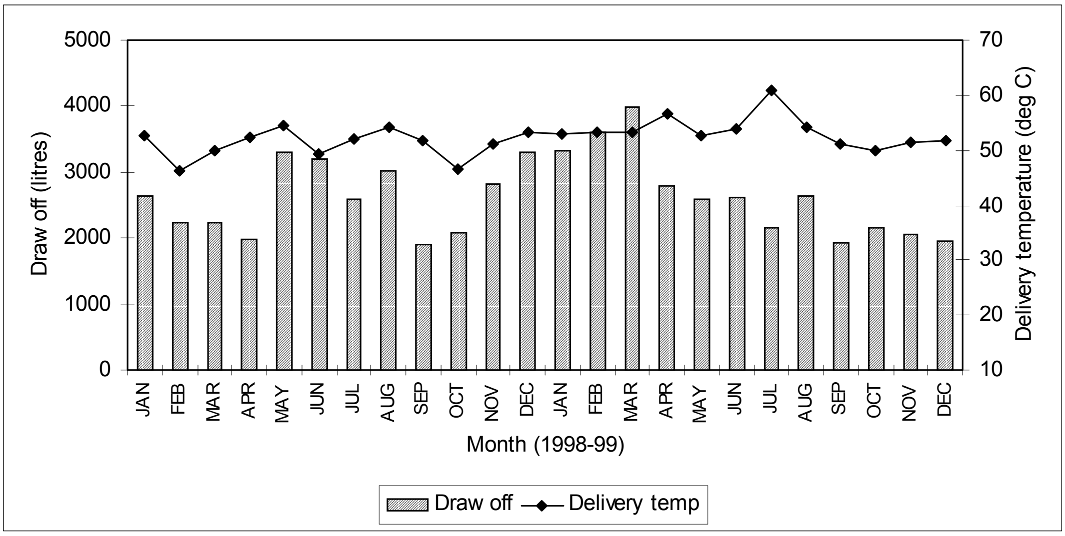


Figure 6.5: Hot water consumption and average delivery temperature

British Gas have suggested that the hot water consumption in a dwelling can be estimated using the formula:

consumption (litres/day) = $38 + 25 \times N$

where:

N is the number of occupants in the household.

The occupancy of the house fluctuates between 4 and 5. Given that the relationship between number of occupants and expected consumption varies directly with occupancy an occupancy figure of 4.5 has been assumed. This results in an expected consumption (assuming 30.5 days in each month) of approximately 4590litres/month. It is clear from Figure 6.5 that the measured consumption is consistently lower than this, and Table 6.3 summarises the average hot water consumption over each of the two years.

Year	DHW consumption (litres/month)	Expected consumption (litres/month)	Difference
1998	2602	4590	-43%
1999	2651		-42%

Table 6.3: Measured and expected hot water consumption

The average domestic hot water supply temperature is also below the commonly assumed value of 60°C. It is typically around 55°C, and on two occasions falls below 47°C.

The next two graphs show how the consumption of hot water is distributed throughout the day. Figure 6.6 covers the winter months, defined here as the period from 1st December through to 31st January.

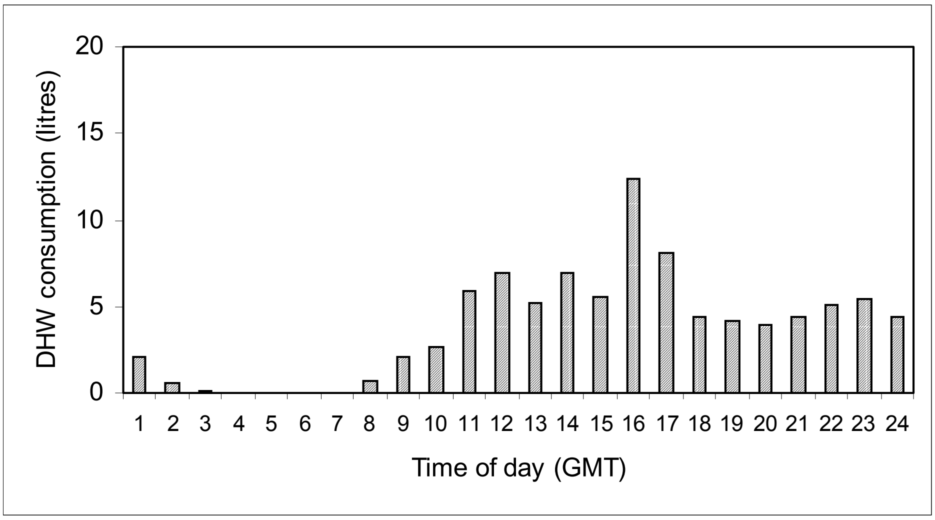


Figure 6.6: Winter hot water consumption profile

Figure 6.7 shows the corresponding hot water consumption profile for the summer months 1st June through to 31st July.

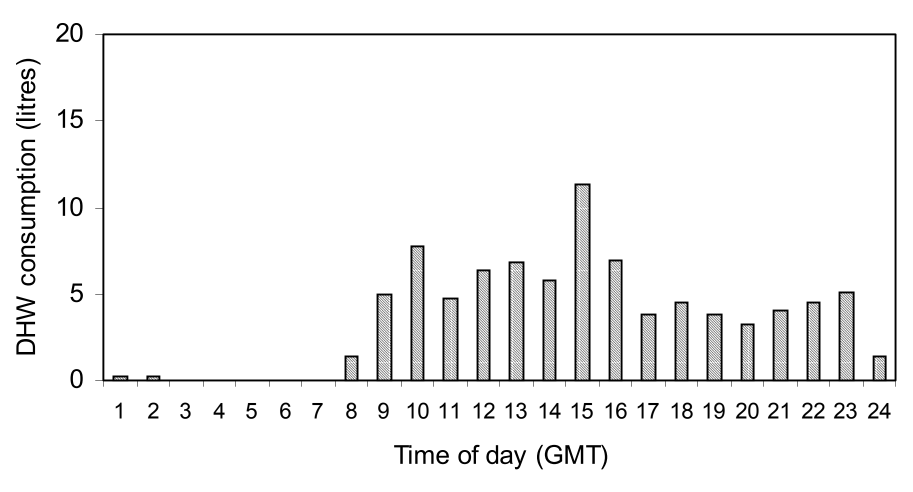


Figure 6.7: Summer hot water consumption profile

The data acquisition systems all run on GMT, and when interpreting Figure 6.7 it is important to remember that BST is one hour ahead of GMT. Applying a simple statistical test to the Winter and Summer profiles indicates that there is no significant change in overall water consumption with season. Both figures show quite clearly that consumption peaks late in the afternoon, an ideal time to make use of solar heated water.

6.4 Evaluating solar contribution and solar fraction

Figure 6.8 shows the monthly contribution from the solar collector, and the estimated energy required for hot water production. As well as the energy which actually comes out of the hot water taps this includes a 15% allowance for system losses. The way in which it is derived is discussed in more detail in Appendix C of this report.

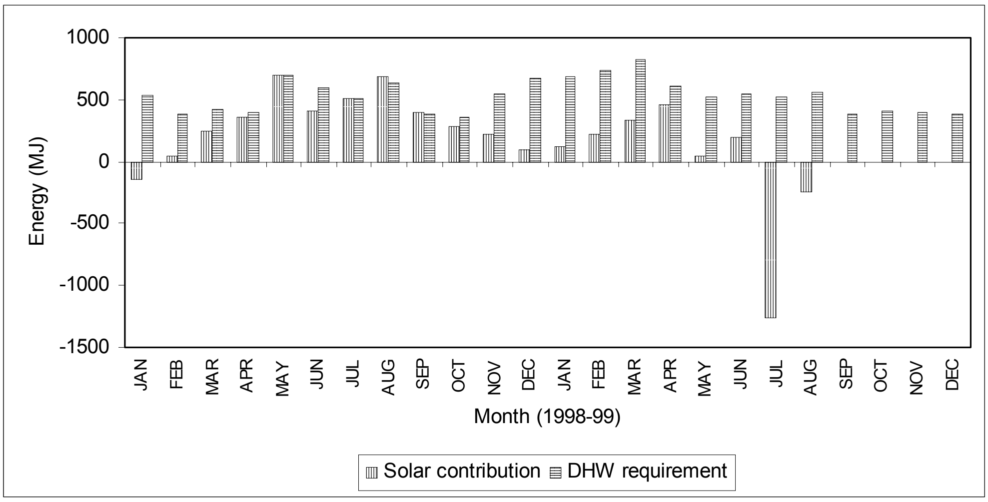


Figure 6.8: Output from collectors and domestic hot water requirement

In an attempt to derive some estimate of the system performance from the available data the monthly totals used to derive Figure 6.8 were recalculated, ignoring negative contributions from the solar collectors. This corresponds to the assumption that, had the collector control system been working more effectively, periods of energy loss could have been avoided simply by turning the collectors off. Figure 6.9 shows the results.

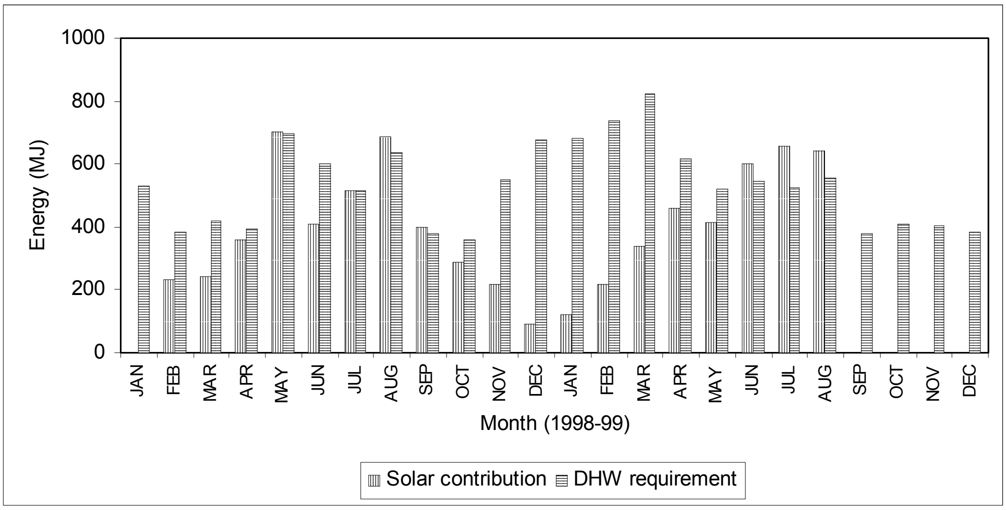


Figure 6.9: Output from collectors (calculated ignoring negative values) and domestic hot water requirement

The total output from the collectors is readily obtained by totalling the monthly outputs shown on Figure 3.8. However, to determine the net benefit from the solar system it is necessary to determine what proportion of the collector output is actually 'useful'. During some months the energy gathered by the solar collectors is greater than the hot water energy actually used. The excess energy is lost from the system - the hot water is stored but never used, and eventually cools due to tank losses. In this situation the excess energy cannot be considered to be of any value, and the delivered energy is simply taken to be the portion of that energy which was actually used. The implications of this assumption are discussed in greater detail in Appendix D of this report. Totalling the resulting useful solar contribution allows the overall energy delivered by the system to be found. Comparing this with the total domestic hot water energy requirement then allows the solar fraction to be determined. Figure 6.10 shows the solar fraction on a month by month basis.

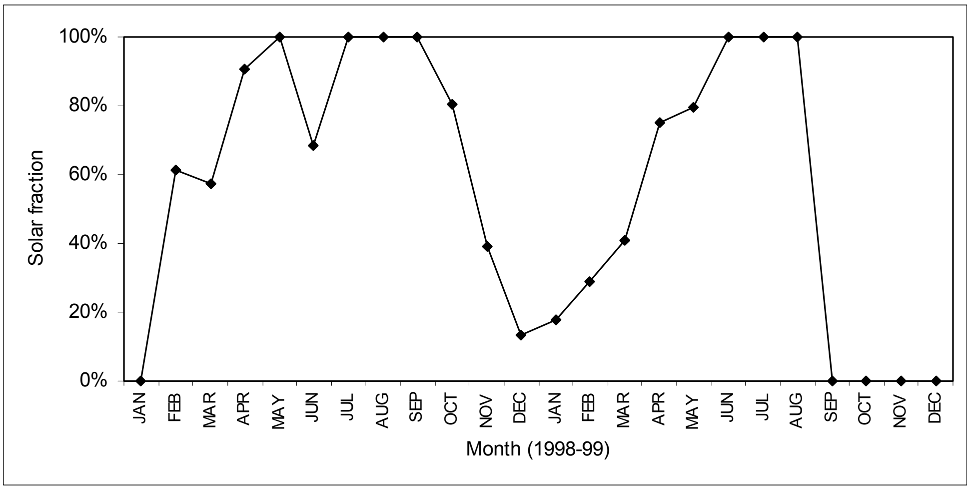


Figure 6.10: Solar fraction

Table 6.4 summarises these results for each of the two years considered. Note that two solar fractions are shown for the second year. The first (shown in brackets) is the fraction of the whole year's hot water energy requirement which was provided by the system. The second figure is the fraction of the hot water energy used during the period for which the system was switched on (January through to August) which was provided by solar.

Year	Solar Collected (MJ)	Useful solar contribution (MJ)	Proportion Useful	DHW energy requirement (MJ)	Solar fraction
1998	4141	4063	98%	6140	66%
1999	3449	3174	92%	(6580) 5003	(48%) 63%

Table 6.4: Useful solar contribution, hot water energy and solar fraction

6.5 Normalising performance to long term average climate

In Section 6.1 it was noted that the solar radiation received during the monitoring period was approximately 5% less than expected from long term climate recordings.

For relatively small changes in radiation such as these it is reasonable to assume that collector output will vary directly with radiation level, and that the measured collector outputs can therefore be increased by the appropriate amount to give an indication of the output that would have been obtained under more representative conditions. Whilst this will give a reasonable indication of what collector output might have been, it is quite possible that not all of the revised output would have been useful. In particular, if the system was already meeting the entire hot water requirement then increasing the collector output will not provide any extra useful energy. In this situation decreasing the collector output also has no effect on the useful solar contribution, until it is decreased beyond the point where the system no longer satisfies the entire requirement.

In view of these considerations it is necessary first to scale the system output and then to re-evaluate the proportion of that output which is useful. Table 6.5 shows the results of carrying out this normalisation for the Tewkesbury site.

Year	Useful solar contribution (MJ)	DHW energy requirement (MJ)	Solar Fraction
1998	4172	6140	68%
1999	3334	(6580) 5003	(51%) 67%

Table 6.5: Useful solar contribution, hot water energy and solar fraction (normalised to 20 year average climate)

For this system the normalisation process makes only a small difference to the solar contribution. The reason for this is that the differences between measured and expected radiation levels are themselves small.

7 SUMMARY AND DISCUSSION

This project has collected data from four dwellings equipped with active solar water heating systems. Over the two year period considered in this report the data has been essentially continuous, with only a few weeks missing from each site.

Unfortunately some of the data actually collected is not of sufficient quality to allow the performance of the respective system to be fully characterised.

The most significant example of this occurs at the Croydon site. From March to August 1998 the output of the system was recorded as negative. This may be due to a problem with the monitoring equipment, but the data which was gathered is entirely consistent, and it seems more likely that it was due to a problem with the system controls. The sensor measuring the temperature of water returning from the collector became unreliable during the first year of monitoring, and failed completely early in the second year. This is clearly a monitoring problem, and without this key measurement it is not possible to deduce system performance. For this reason solar system performance results from Croydon are presented only for the period from September 1998 to May 1999.

At the Troon site the recorded output of the collector became unrealistically high during the second year of monitoring, to the extent that its efficiency exceeds 100% for almost half the year. This is clearly physically impossible, and it would be misleading to incorporate this data into an estimate of overall solar contribution. For this reason solar system performance data from Troon is presented only for the first year of the monitoring period.

Finally, there were two system problems at the Tewkesbury site during the second year of monitoring. Large negative solar contributions were recorded during July and August, and these have been ignored in the results presented here. The measured data indicates that there was no heat output from the collector system for the last four months of the year. Further examination reveals that there was no flow through the collector, and that the flow and return temperatures recorded are consistent with this. The most likely explanation is that the system was switched off for the last four months of the trial.

7.1 Collector performance

The output of each collector system was calculated by the data acquisition system, which measured the flow and return temperatures and the volumetric flow through the collector every five seconds, and integrated the resulting energy output over each 15minute recording interval.

The long term efficiency of each system has been determined by comparing the monthly output of each system with the total incident radiation. Table 7.1 summarises the total energy collected and working efficiencies measured.

		Total energy collected (MJ)	Collector long-term efficiency
LUTON	1998	3930	25%
	1999	4311	
CROYDON	1998	1600	48%
TROON	1998	5255	41%
TEWKESBURY	1998	4141	31%
	1999	3449	

Table 7.1: Energy provided by collectors and corresponding efficiencies

The efficiencies shown in Table 7.1 are working values. The figures obtained in this trial cannot be compared directly with the values from laboratory tests. The temperature at which water was supplied to the collectors will obviously have varied significantly over the course of the year. Furthermore, it is highly likely that there will have been periods when the collectors were not able to extract the maximum possible benefit from incident radiation, due to utilisation issues.

7.2 Hot water consumption

Hot water consumption has been monitored at 15 minute intervals. As well as total consumption, this allows daily consumption profiles to be generated.

Table 7.2 shows the average hot water consumption in each of the dwellings monitored, and also the expected consumption, calculated using a formula provided by British Gas.

		Measured consumption (litres/month)	Expected consumption (litres/month)	Difference
LUTON	1998	2893	4209	-31%
	1999	3248		-23%
CROYDON	1998	1615	2684	-40%
	1999	1556		-42%
TROON	1998	2023	4209	-52%
	1999	2072		-51%
TEWKESBURY	1998	2602	4590	-43%
	1999	2651		-42%

Table 7.2: Hot water consumption

The table reveals that the consumption observed in each dwelling is remarkably consistent from year to year, and also that it is consistently less than expected. Table 7.3 shows the corresponding mean delivery temperatures.

		Delivery temperature (°C)
LUTON	1998	49.8
	1999	49.6
CROYDON	1998	54.3
	1999	56.4
TROON	1998	43.1
	1999	44.1
TEWKESBURY	1998	51.2
	1999	53.5

Table 7.3: Hot water delivery temperatures

It is remarked that the delivery temperatures accepted by the occupants of the monitored dwellings are consistently lower than the normally assumed value of 60°C. Troon, which has consumption much lower than expected, is also seen to have low delivery temperatures, meaning that the energy required to provide hot water will be particularly low.

Daily profiles have been calculated by averaging the measured consumption over two winter months (December and January) and two summer months (June and July).

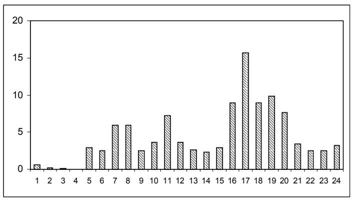
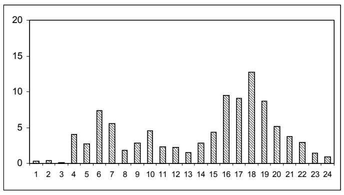
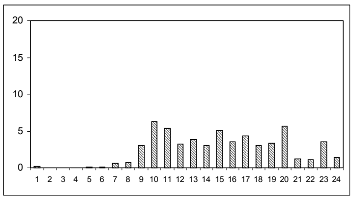
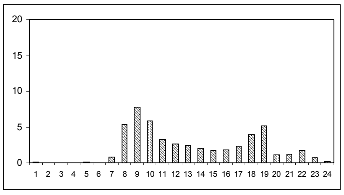
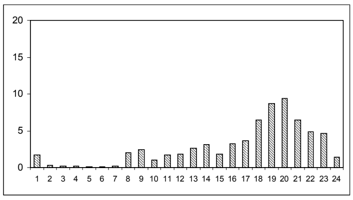
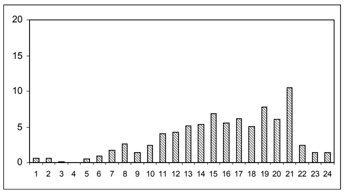
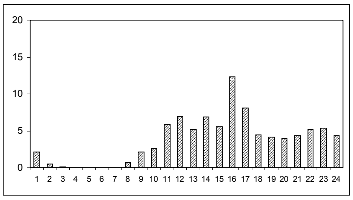
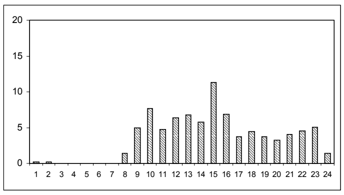
	WINTER	SUMMER
LUTON		
CROYDON		
TROON		
TEWKESBURY		

Table 7.4: Profiles showing hot water consumption (in litres) over the day (note that all times are GMT)

The table shows that while there are significant variations in profile between sites there is little variation from winter to summer at each site. A simple statistical test has been used to confirm that the variations in mean consumption observed between the summer and winter are so small that they could have occurred purely by chance at all the sites.

7.3 Proportion of output used and solar fraction

To determine the net benefit from the solar system it is necessary to determine what proportion of the collector output is actually ‘useful’. During some months the energy gathered by the solar collectors is greater than the hot water energy actually used. The excess energy is lost from the system - the hot water is stored but never used, and eventually cools due to tank losses. In this situation the excess energy cannot be considered to be of any value, and the delivered energy is simply taken to be the portion of that energy which was actually used. The implications of this assumption are discussed in greater detail in Appendix D of this report. Totalling the resulting useful solar contribution allows the overall energy delivered by the system to be found.

		Useful solar (MJ)	Fraction Useful
LUTON	1998	3641	93%
	1999	4236	98%
CROYDON	Sep ’98 - May ‘99	1613	64%
TROON	1998	2885	55%
TEWKESBURY	1998	4063	98%
	1999	3174	92%

Table 7.5: Useful energy provided by systems

When interpreting the results shown in the table it must be remembered that the system at Tewkesbury was switched off from September to December 1999, and that the figure shown relates to energy gathered from January to August.

By showing what fraction of the energy collected was actually used Table 7.5 also reveals how much energy was discarded. This in turn provides an indication of how appropriately each system was sized. The systems at Luton and Tewkesbury both seem to have been sized in such a way that almost all of the energy they provide is useful. The size of the system at Troon is such that almost one half of the energy gathered is not used. However, it has already been observed that the households at Croydon and Troon both had a much lower water consumption than expected, and this will to some extent account for the rather large proportion of the collected energy which had to be discarded.

Figure 7.1 shows the annual useful energy provided by each system graphically. Since a full year’s data is not available from the Croydon site it is not shown on the figure. Likewise, since data for 1999 is not available for the systems at Troon and Tewkesbury only their results for 1998 are shown.

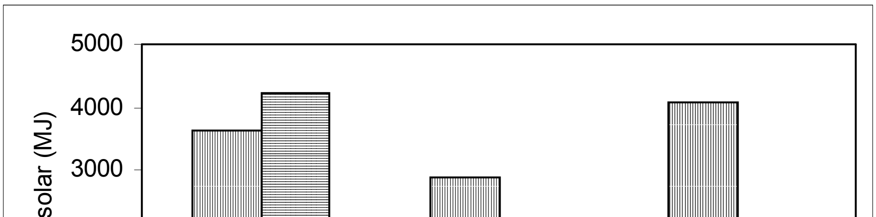


Figure 7.1: Useful energy provided by systems

Comparing the useful part of the collected energy with the total domestic hot water energy requirement then allows the proportion of the hot water load satisfied by the solar system, or ‘solar fraction’ to be determined. Table 7.6 summarises the results. Note that for the Tewkesbury site two solar fractions are shown for 1999. The first (shown in brackets) is the fraction of the whole year’s hot water energy requirement which was provided by the system. The second figure is the fraction of the hot water energy used during the period for which the system was switched on (January through to August) which was provided by solar.

		Solar Fraction
LUTON	1998	55%
	1999	58%
CROYDON	Sep ’98 - May ‘99	63%
TROON	1998	76%
TEWKESBURY	1998	66%
	1999	(48%) 63%

Table 7.6: System solar fractions

7.4 Normalising to long term climate

Inevitably, the solar radiation levels experienced during the monitoring period were slightly different to those expected over the longer term. The observed radiation levels differ from 20 year long term average data taken from meteorological stations near each of the monitoring sites by between –18% (implying that the radiation observed was less than the expected value) and +11% (implying that the observed levels were above those expected).

For relatively small changes in radiation such as these it is reasonable to assume that collector output will vary directly with radiation level, and that the measured collector outputs can therefore be increased by the appropriate amount to give an indication of the output that would have been obtained under more representative conditions. Whilst this will give a reasonable indication of what collector output might have been, it is quite possible that not all of the revised output would have been useful. In particular, if the system was already meeting the entire hot water requirement then increasing the collector output will not provide any extra useful energy. In this situation decreasing the collector output also has no effect on the useful solar contribution, until it is decreased beyond the point where the system no longer satisfies the entire requirement. In view of these considerations it is necessary first to scale the system output and then to re-evaluate the proportion of that output which is useful. Table 7.7 shows the resulting useful solar energy and solar contributions. Again two figures are quoted for the Tewkesbury site during 1999.

		Useful solar (MJ)	Solar Fraction
LUTON	1998	4038	61%
	1999	4538	62%
CROYDON	Sep ’98 - May ‘99	1821	71%
TROON	1998	2898	76%
TEWKESBURY	1998	4172	68%
	1999	3334	(51%) 67%

Table 7.7: Useful energy provided by systems and resulting solar fraction scaled to long term average solar radiation levels

Once again Figure 7.2 shows the energy provided by each of the systems for which whole year’s data are available graphically.

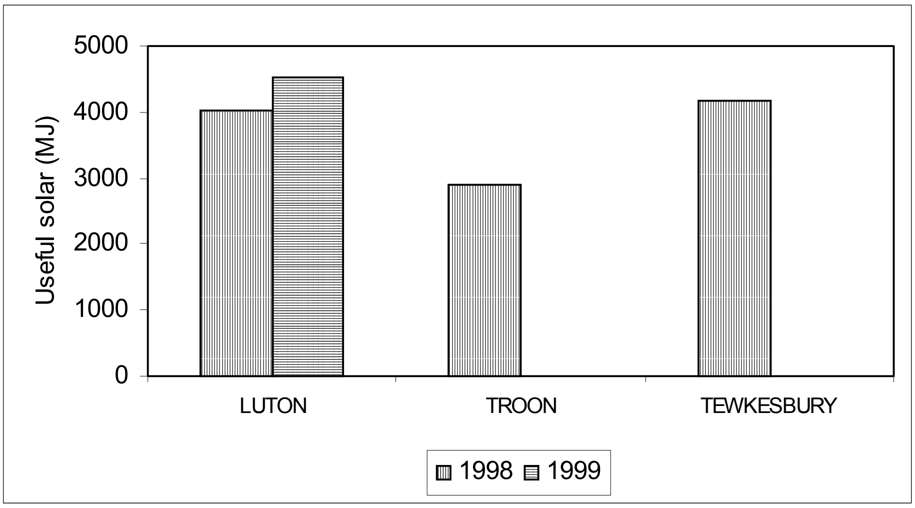


Figure 7.2: System output scaled to long term average solar radiation

7.5 Comparing between systems

It is clearly of interest to compare the performance of the systems monitored, and a series of measures of performance has already been generated which could be used for this purpose.

Perhaps the most appealing is the solar fraction, since it has an immediate interpretation. However, it depends critically on the hot water demand placed on the system. If, as in the case of the Troon site, the hot water load is very low then the solar fraction will be high, even though a large proportion of the energy collected is being discarded and the useful energy contribution from the system is therefore being reduced.

The useful energy delivered by the system also represents a way of comparing between systems. This output can readily be normalised to account for short term variations in climate, and the results shown in Table 7.7 and on Figure 7.2 provide a good indication of how each system might be expected to perform in the long term. However, they do not allow comparisons to be made between systems, as the radiation levels expected at each site are, of course, different. To compare between systems it is necessary to generate a measure of performance which is independent of the actual solar radiation incident on each installation.

Collector efficiency provides a way of comparing between individual collectors which is independent of radiation level, but it is of little value for comparing the performance of installed systems. The reason is simple: one collector design may be less efficient than another, but if it is cheaper to manufacture then a larger area can be installed for a given cost.

In view of these problems a ‘solar collection factor’ has been calculated for each system, by dividing the useful solar output of each system by the amount of radiation incident. It has dimensions m^2, and can be interpreted as the area of ‘perfect’ solar collector which would be required to provide the output measured, where a perfect collector is 100% efficient and all the energy it produces is useful. The solar collection factor can also be interpreted as the collector efficiency multiplied by the area of collector installed, with the *caveat* that it is actually calculated from the amount of useful energy provided, rather than the total collector output. Figure 7.3 shows the results for the systems from which a whole year’s data are available.

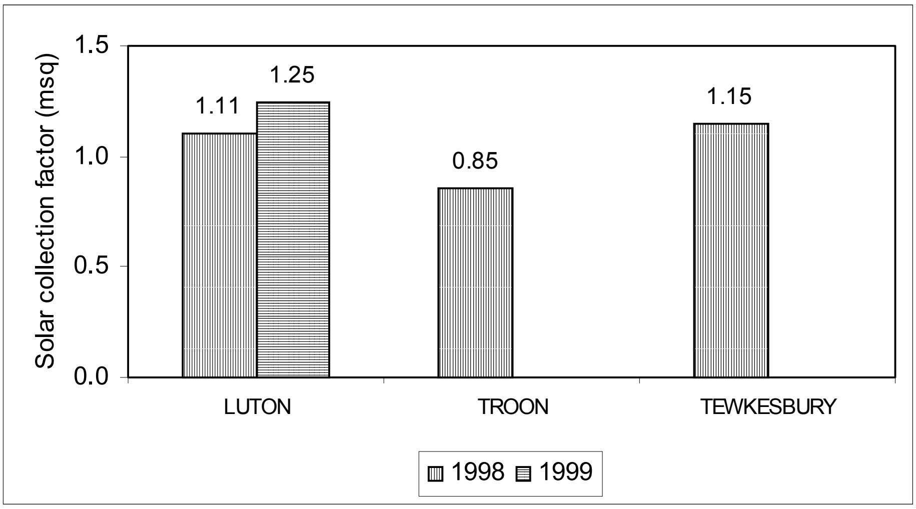


Figure 7.3: Solar collection factor for each system

Because the solar collection factor is based on useful output it still does not give a fully representative measure of the relative quality of the systems. It has been seen that each installation was subjected to a different run off pattern, and this will inevitably have influenced the performance of each system. The only way to generate a genuine comparison between systems is to subject each to the same demand profile under identical climatic conditions.

REFERENCES

[1] Equipment recommendations for monitoring active solar water heating installations. Chris Martin. Report to ETSU. March 1996.

[2] Monitoring active solar water heating installations: Analysis of preliminary data from Luton, Croydon and Troon. Chris Martin. Report to Solar Trade Association. August 1997.

[3] Designers' handbook of UK data for Solar Energy applications. Prof John Page and Ralph Lebens. Report to ETSU. 1984.

APPENDIX A: DATA ORGANISATION AND FORMAT

The disk which accompanies this report contains all of the data gathered during the project, and the results files from the analysis described in the main body of the report. The purpose of this Appendix is to allow anyone wishing to carry out further analysis to make use of that data.

A1 Measured data

The directory RAW_DATA on the compact disk contains the data collected by the Solar Trade Association. Files from the four sites are in four subdirectories called CROYDON, LUTON, TROON and TEWKES.

There were a number of minor problems when these files were generated, and as a result some data cleaning was necessary. The directory CLN_DATA contains the same subdirectories, which in turn contain the cleaned data from each site.

The files are named using the following convention:

STA A DD M Y . DAT

where:

STA indicates that the data is from this project,

A is the site identifier. Four of these have been used:

C - Croydon

L - Luton

T - Troon

W - Tewkesbury

DD is the start day of the data contained in the file

M is the start month of the data with January through to September coded as 1 through 9, October as A, November as B and September as C

Y is the start year of the data, with 1997 coded as 7 and so on. 2000 is coded as 0.

As an example, the first datafile collected from Luton, which starts on 17th May 1996 is called

STAL1756.DAT

The clean version of the data is in the directory \CLN_DATA\LUTON.

Each line of the measured data contains results from one 15 minute logging period. Table A1 describes how the values on each line, which are delimited by commas, are interpreted.

Entry	Quantity	Units
1	Date	DD/MM/YYYY
2	Time	Decimal hour
3	Solar radiation	W/m^2
4	External air temperature	°C
5	Collector feed temperature	°C
6	Collector return temperature	°C
7	Collector flow	Litres
8	Collector heat delivered	kJ
9	Domestic hot water temperature	°C
10	Domestic hot water flow	Litres

Table A1: Format of recorded data

A2 Master files

Data was collected from each site approximately once a month. In order to carry out the analysis described in this report the resulting files were concatenated into a single 'master' file for each site. These are located in the directory \MASTERS. They are named as follows:

STAC.DAT - Data from Croydon

STAL.DAT - Data from Luton

STAT.DAT - Data from Troon

STAW.DAT - Data from Tewkesbury

The format of these files is the same as for the measured data, with the delimiters changed from commas to spaces.

A3 Results files

In order to derive the long term averages and totals presented in the main body of this report the data recorded at 15 minute intervals was processed to generate files containing daily and monthly results.

These files are located in the directory \SUMMARY. The files are named using the following convention:

STA A . EXT

where:

STA indicates that the data is from this project,

A is the site identifier. Four of these have been used:

C - Croydon

L - Luton

T - Troon

W - Tewkesbury

EXT is the extension, which is DAY for daily results and MON for monthly.

The format of the processed data follows closely the format of the incoming quarter hourly data, and is summarised in Table A2.

Entry	Daily data (extension .day)	Monthly data (extension .mon)
1	Day number (1st January 1996 = day 1)	Month number (January 1996 = month 1)
2	Proportion of expected data actually found	
3	Total solar radiation (MJ/m^2)	
4	Mean external air temperature (°C)	
5	Collector feed temperature (°C)	
6	Collector return temperature (°C)	
7	Total collector flow (litres)	
8	Total collector heat delivered (MJ)	
9	Total collector heat delivered taking only positive contributions (MJ)	
10	Mean domestic hot water temperature (°C)	
11	Total domestic hot water flow (litres)	
12	Domestic hot water energy requirement (MJ)	
13	Flow weighted average domestic hot water temperature (°C)	

Table A2: Format of daily and monthly summary files

APPENDIX B: HANDLING MISSING DATA

It is clear from Figures 3.1, 4.1, 5.1 and 6.1 in the main report that there are some periods where data has been lost. This may be because the system was taken down for maintenance, because a data card was temporarily removed from the logger, because a card was changed late and data lost, or because there was an error reading the card. It is therefore essential that the data processing software used to generate the daily and monthly results files can cope with periods of missing data.

When calculating averages the result is found by dividing the total of all the data values recorded by the number of values. In this case the average over a period in which some data was missing is still a good summary of the data. This is equivalent to assuming that the missing data should be replaced with the mean value of the data which was actually recorded, a reasonable approach in the absence of any further information.

When the total values are produced they are normalised based on the number of data values expected over the totalling period and the number actually found. In the case of a daily calculation the expected number of lines is always 96, and the normalisation is calculated accordingly. In the case of monthly data the expected number of lines is given by the number of days in the month times 96. Once again, this is equivalent to assuming that the missing data has been replaced by the mean value of the data which was recorded. In the case of daily data the results should be treated with some caution. Consider the case where the logger was switched off during the daylight hours. Then the estimated total solar radiation will be zero, not a realistic result. However, for monthly data, or days where only a few readings are missing, the scheme works well. A good example can be seen in the Luton dataset, where roughly half the data for November 1999 is missing. In this situation the program calculates the average values over the latter half of the month. The totals of solar radiation, collector flow and heat production and hot water run off are adjusted by a factor of approximately two to make them directly comparable with results from succeeding months.

If less than 25% of the data expected within a given analysis period is present then a blank record is written to the results file, which contains just the month or day number and the proportion of expected data found. The table below shows this for monthly analysis of the Croydon data.

10	0.11										
11	1.00	94825	5.55	11.71	11.47	3099	-22542	48.35	2091	386494	54.7
12	0.03										
13	0.98	70546	2.11	9.87	11.08	2432	-18436	48.57	2264	419659	54.9
14	1.00	102072	6.61	13.18	12.91	4198	-33328	47.88	1995	361204	53.8
15	1.00	307649	8.59	21.72	21.57	20706	168191	48.75	1981	366604	54.8
16	1.00	488316	9.03	28.51	28.47	39252	342738	50.41	1308	251968	56.6

Table B1: Monthly results from Croydon site, showing missing records due to insufficient data

There are also rare occasions when data is missing from just one channel. The table below shows data recorded at the Luton site during the afternoon of the 6th November 1996.

```
06/11/1996,14.7500,28.2,13.83,31.34,30.85,0,0.00,26.54,0
06/11/1996,15.0000,25.0,13.88,28.03,26.02,0,0.00,19.80,0
06/11/1996,15.2500,17.5,13.16,25.59,23.23,0,0.00,99999.9,1
06/11/1996,15.5000,16.9,12.66,23.77,21.46,0,0.00,99999.9,0
06/11/1996,15.7500,8.8,12.05,22.36,20.09,0,0.00,99999.9,24
06/11/1996,16.0000,5.3,11.71,21.17,18.93,0,0.00,99999.9,0
06/11/1996,16.2500,2.4,11.27,20.14,17.94,0,0.00,31.15,0
06/11/1996,16.5000,0.9,11.10,19.27,17.18,0,0.00,31.17,0
```

Table B2: Data from Luton site on afternoon of 6th November 1996

Here the hot water temperature sensor reading has not been made successfully on four successive scans, at 3:15, 3:30, 3:45 and 4:00pm. The data logger has indicated this by recording the dummy value 99999.9. The way in which this is handled is simply an extension of the procedure described for cases where one or more whole data records are missing. A separate counter is maintained for each channel, and thus when the normalisation process described above is carried out it is based on the number of good readings obtained for that channel. In this way the type of problem shown in the table is catered for.

APPENDIX C: DETERMINING HOT WATER DELIVERY TEMPERATURE AND ENERGY

It is not generally practical to install a temperature sensor directly into a domestic hot water tank. In the installations described here the sensor has been placed in the pipe that leaves the tank. This means that during periods when no hot water is drawn off the sensor will cool (as the water in the pipe cools) and its reading will no longer be representative of conditions in the tank. This is not a problem, as the temperature of the water is unimportant when none is being used.

When water is drawn off the cold water in the pipe is quickly replaced by hot water from the tank, and the temperature of the sensor returns to a representative value. Because this happens relatively quickly it might be assumed that the sensor cooling effect described above will not cause any errors, and that the hot water energy can be calculated simply by combining the flows and temperatures recorded each quarter of an hour. However, the temperature value actually recorded is an average of fifteen values taken over the quarter hour period preceding the time at which the reading is logged. Consider the situation in which hot water is run off during the last five minutes of the quarter hour. Even if the temperature in the pipe changed instantaneously, the value recorded would be an average including data from the first ten minutes during which time the sensor was cold. If the hot water temperature was actually 60°C but the sensor had previously cooled to 30°C, the average over the whole quarter hour would be logged as only 40°, a very significant error.

Figure C1 demonstrates this problem using data recorded at the Luton site.

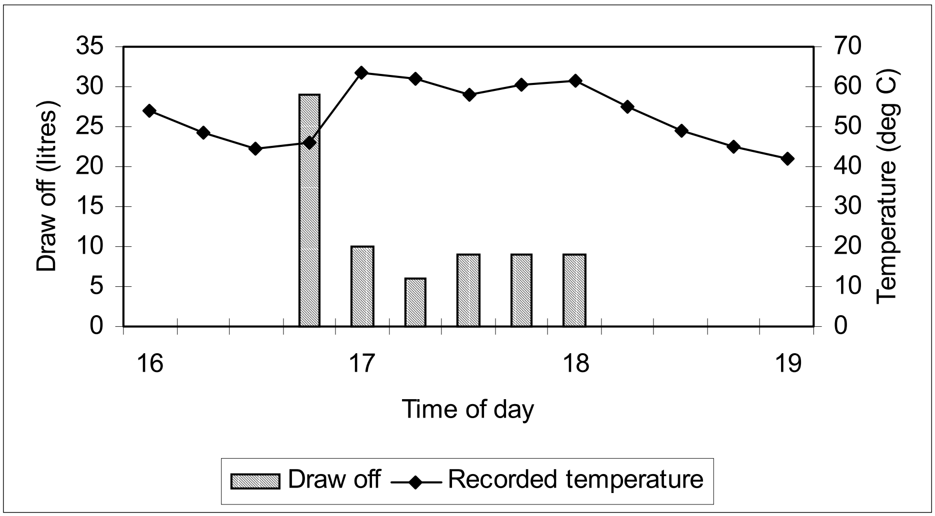


Figure C1: Hot water flow and temperature data

Over the afternoon there had been no hot water use, and the temperature sensor had cooled to approximately 45°C. A period of hot water usage starts with the data recorded at 4:45pm, indicating that water was drawn off at some stage between 4:30 and 4:45pm. However, the hot water temperature recorded at this stage is only just above 45°C. Subsequent data shows that the temperature in the pipe soon rises to over 60°C, indicating that this is the actual temperature in the tank. Clearly if the hot water heating energy was calculated from this data simply by combining the flow and temperature data recorded at 4:45pm there would be a significant underestimate of that energy.

The solution adopted is to read the hot water temperature from the following timestep, (in this case 5:00pm) and combine it with the measured flow. The only situation in which this may cause errors is when the run off stops, as the succeeding temperature will be slightly depressed as the cooling cycle starts again. However, the sensors are insulated and are surrounded by a mass of water so this cooling is relatively slow, and the error is small. This is confirmed on Figure C1, where the cooling which occurs during the fifteen minutes after flow stops is seen to be only a few degrees. This effect will always lead to a small underestimation in the energy load associated with a given hot water draw off.

In order to calculate the energy required to heat the domestic hot water to its delivery temperature it is necessary to assume a starting temperature. The figure taken here is 10°C. This turns out to be very close to the annual mean external temperature.

The result of this calculation is the energy required to heat the water which was actually delivered, and takes no account of the system losses. If the solar collector was not present fossil fuel would be required not only to heat the water, but also to offset the system losses. In the past these losses have been estimated by BRE to be approximately 15%. During the first summer in which data was gathered (1996) the householder at the Luton site switched off the auxiliary heating and used only solar heated hot water. Preliminary analysis of data from that installation revealed a solar fraction that hovered between 99 and 100%, suggesting that the assumption of 15% losses was indeed a good one.

It is of interest to calculate a mean temperature at which hot water has been provided. It is clear from the discussion above that there is little point in simply examining the time average of the sensor reading, as this would include long periods during which the sensor was cooling, and give an erroneous result. Instead a flow weighted mean is calculated by summing the flow multiplied by the delivery temperature (derived as described above). Before the data is written to the file the total is divided by the total flow accumulated over the period, to give a mean delivery temperature.

APPENDIX D: DETERMINING THE PROPORTION OF COLLECTOR OUTPUT WHICH IS USEFUL

The instrumentation specified for this project did not include a means of measuring directly the auxiliary energy used to heat domestic hot water. There were two reasons for this:

- the source of auxiliary energy may vary from one installation to the next. It could be an electrical immersion heater, a pumped water circuit from a conventional boiler, a gravity fed circuit from a conventional boiler or a combination boiler which heats hot water as and when required. It would therefore not have been possible to produce a unified specification for the equipment required for monitoring

- some of these sources of energy are notoriously difficult to meter. In particular it is very difficult to measure the flow rate in a gravity fed system without disrupting the performance of the system.

In light of these considerations it was decided that hot water consumption and solar collector output would be measured, and the energy required from the auxiliary source inferred by subtraction. This approach has the shortcoming that it is necessary first to determine the proportion of the solar energy collected which was actually useful in displacing auxiliary heating.

The analysis described in this report worked with totals of collector output and water consumption data computed over each calendar month. For months where the collector output is less than or equal to the demand it is assumed to be entirely useful. If the solar contribution is less than demand the auxiliary requirement is calculated as the difference between the two values, and the solar contribution assumed to be entirely useful. If the collector output is equal to or greater than the demand the auxiliary energy requirement is taken to be zero and the solar fraction becomes 100%. The useful solar contribution is then taken to be equal to the hot water requirement. Any excess solar contribution is assumed to be lost.

This analysis is clearly flawed in a number of respects:

- the use of calendar months has no physical significance: the collector and hot water systems do not know which month it is ! Furthermore, the months are of varying lengths

- in a month where the solar contribution is, for example, exactly equal to the hot water requirement this is likely to have occurred as a result of the solar contribution being larger than the requirement on some days, and smaller on others. In this situation it may or may not be reasonable to assume that the excess has been successfully stored for use on days when there is a deficit

- the analysis used in this report is therefore equivalent to assuming that the system provides perfect storage over the course of each calendar month, and that any excess energy is dumped at the end of the month, clearly not an entirely realistic scenario.

It is clear that the exact way in which excess energy is used depends critically on the proportion of it which can be stored. In order to investigate the effect of storage on useful solar contribution a simple calculation was carried out using daily totals of collector output and hot water demand from the Luton site.

The type of analysis described above was carried out for each day. If the solar contribution was greater than the hot water requirement the excess energy was placed in store. If the solar contribution was less then it was assumed to be used in its entirety, and the deficit made up as far as possible from the energy in the store. Most critically, energy was assumed to be lost from the store overnight at a rate determined by the amount being stored, with only a fixed fraction being retained until the next day. The amount of energy which could be transferred to the store was limited to 32MJ, equivalent to raising the temperature of a 150litre tank of water by 50°C.

A moment's thought indicates that if the fraction of energy retained is 100% this is equivalent to assuming that the system has perfect storage. Provided that the capacity of the store is not exceeded all solar energy collected will eventually be useful. This is close to the assumption made in the main body of this report, with the exception that in that analysis any stored energy is discarded at the end of each month. Conversely, if the fraction retained overnight is zero excess energy collected on days when solar output exceeds demand is wasted, and the proportion of collected energy which is actually useful will fall below 100%. The graph below shows the magnitude of this reduction for the Luton site for each month of the two year analysis period.

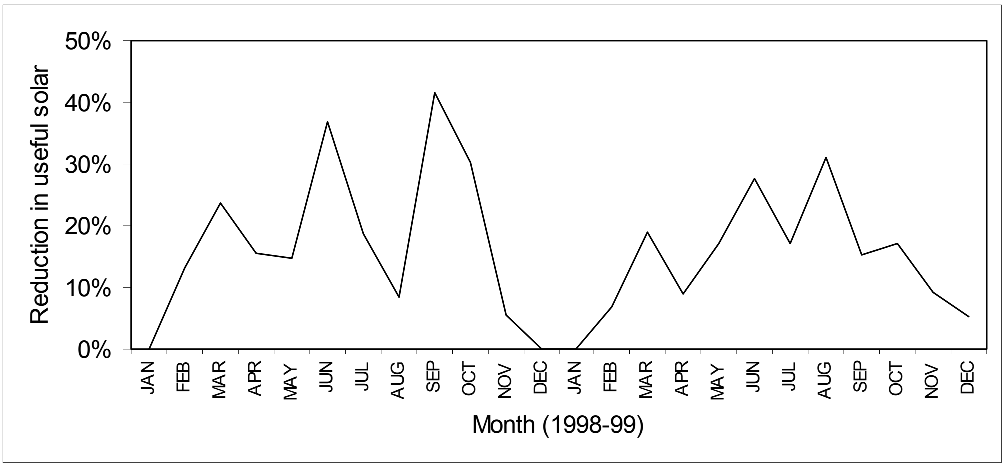


Figure D1: Reduction is useful solar energy when overnight storage is eliminated

In producing this figure the useful solar contribution was totalled over each calendar month, but the energy in storage was allowed to be carried over from one month to the next.

As expected, the figure reveals that in winter removing storage has little or no effect in winter: the output of the collector is small compared with hot water demand, and energy is used as it is gathered. In the brighter summer months such as August 1998 the effect is also reduced because so much energy is available that whether the previous day's has been stored becomes immaterial. The effect of storage becomes most critical during months when there is just enough collector output to satisfy the overall demand. Then it is vital that excess energy from one day can be effectively stored for use on the next.

The situation in a real installation will lie somewhere between these two extremes. Solar cylinders tend to be well insulated, and it is estimated that the fraction of stored energy retained overnight is likely to be between 70 and 90%.

Figure D2 shows the effect of varying the fraction of energy retained overnight during July 1999, a typical month.

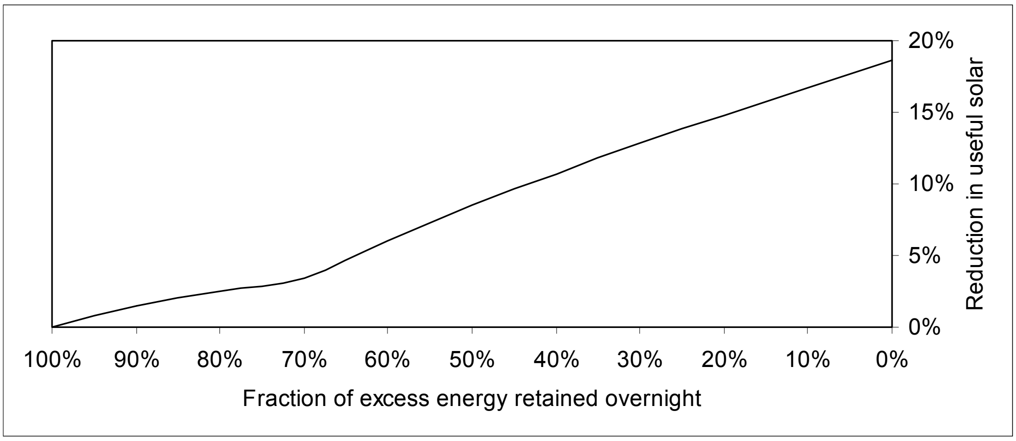


Figure D2: Impact of fraction of energy retained overnight on useful solar

The curve is relatively flat until the fraction of energy retained overnight falls below about 70%. If the actual figure is indeed between 70 and 90% we conclude that the error introduced by the analysis method used in the main body of this report is likely to be less than 5%.