

CITY OF CAPE TOWN
LOW-COST URBAN HOUSING UPGRADE
KUYASA, KHAYELITSHA

Solar Water Heater Model



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1. Background

The City Of Cape Town's Low-Cost Urban Housing Upgrade Project in Kuyasa, Khayelitsha has included the supply and installation of domestic solar water heaters (SWHs) on 10 houses which previously had no hot water on demand. One of the intentions of the project is to develop a basis for understanding and predicting the performance of the SWHs to a larger sample of houses. The primary mechanism for the extrapolation of the experience on the 10 houses in the baseline study is a model which can predict their performance for the larger sample.

AGAMA Energy was appointed by SouthSouthNorth, on behalf of the City of Cape Town, to develop this model. This report documents the development of the model and discusses its applicability.

2. Scope

The model is being developed in order to accurately determine the amount of hot water available at each house with a close-coupled solar water heater (SWH), for any angle of tilt and azimuth¹. Specifically, the model is to predict the energy in the hot water that is available to each household over a year. The SWHs have a collector area of 1.4 m², and a hot water storage tank of 100 litres.

The numerical model is validated by draw-down tests performed on the SWHs installed in Kuyasa, Khayelitsha.

3. Methodology

The approach taken has been that of a spreadsheet-based model, as opposed to a numerical, software based approach. This 'static' approach has inherent disadvantages, particularly given the high quality of software that exists to perform solar water heating design modelling. The primary disadvantage lies in the static approach not being capable of modelling the mass flow rate of the water as it moves between the SWH's collector and storage tank, this parameter being paramount to further heat flow definition. These additional definitions do thus not flow from the static model. In developing the static model, then, a more global approach of defining a system efficiency was taken. This procedure is detailed in Section 4, and Appendices 1 and 4 (Modelling algorithms and model parameters definition, respectively).

The model is available as an Excel spreadsheet, which can be read in conjunction with this document. The model has been limited to determining the volumes of hot water available on a daily - as opposed to hourly - basis, in line with the need to approach the problem at a more global level.

Section 4 describes the model in detail. In particular, the following parameters and how they related to the model are described:

- The collector area of the SWH, in square metres.
- The hot water storage tank volume.
- The azimuth angle, i.e. the rotation of the SWH away from true north.
- The tilt angle, i.e. the inclination of the SWH from the horizontal.

¹ 'Tilt' refers to the SWH collector's angle from the horizontal, while 'azimuth' refers to the deviation of the SWHs direction from true north.

- The cold water temperature at the inlet to the SWH.
- The hot water temperature measured inside the water storage cylinder.
- The daily horizontal solar radiation, measured in kW/m².
- The daily hot water consumption.
- The daily system efficiency, calculated using the daily hot water demand².

The range in actual daily system efficiencies is forced to fit within a range of system efficiencies, by defining the minimum and maximum efficiencies that are applicable. This procedure is discussed in Section 4.3.

The input data are based on measured parameters in four houses (see Section 4.1 below) with close-coupled SWHs in Kuyasa, covering a period of between 129 in one house (56013) and 145 days for the other three used in developing this model. This difference is due to the data logger attached to house 56013 not providing good quality data over the entire period.

4. Model development

4.1 Approach and criteria for SWH selection

Of the ten SWH systems comprising the pilot study, only the close-coupled systems were included for the modelling process. In addition, data from only those houses with a temperature sensor in the hot water storage tank were included in the sample since the model is based on the hot water available in the horizontal water storage cylinder. Temperature sensors were located in the thermostat housing, which are located either halfway or two-thirds of the way up the side of the storage cylinder. Although there would typically be a vertical temperature profile within the hot water cylinder, this position was considered as being representative of the overall temperature within the cylinder.

A final screening involved identifying houses with noticeable electric backup heating usage, and discarding. This resulted in four houses being included in the modelling process: houses 56013, 56586, 54610 and 55747.

The data from one house, House 56013, was used to develop the overall lower bound on the system efficiency, which was assumed to be the same for all the installed close-coupled systems (refer to Section 4.3.2). This assumption is made on the basis that the SWHs are of near-identical size and design. Calculation of daily system efficiencies with further statistical processing on three additional houses, Houses 56586, 54610 and 55747 then defines the upper bound of system efficiencies (refer to Section 4.3.3). These three houses were selected because the hot water temperatures was being measured in the storage tank, a key parameter in being able to determine the available hot water in the system.

Results from these four houses were then used to develop an average annual energy saving, per system, with the energy modelled being that available in the hot water storage cylinder. This energy content is graphically illustrated in Figure 4-1.

² The system efficiency varies considerably according to both the volume of water consumed, and the time over which it is consumed, i.e. the daily hot water consumption profile

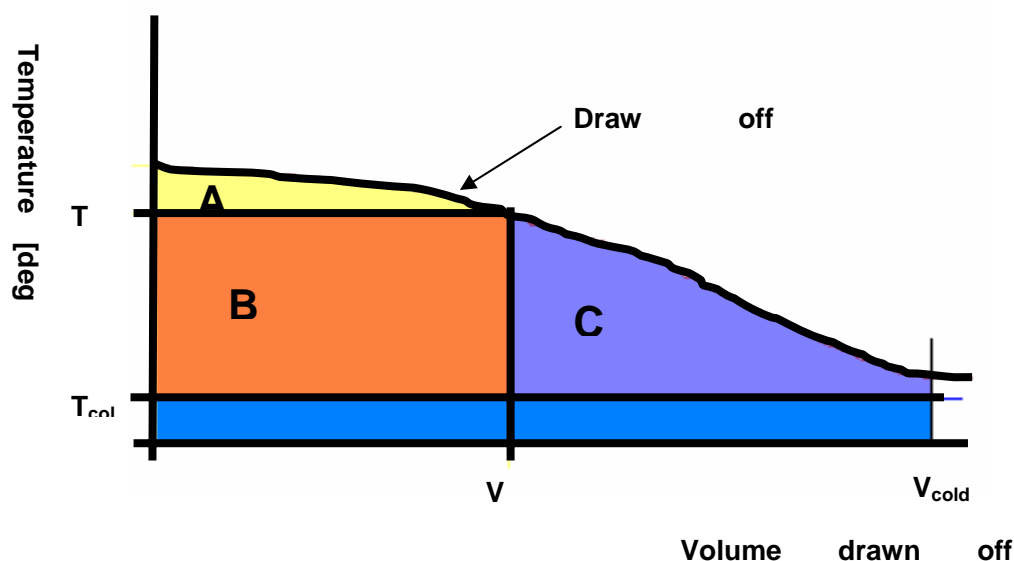


Figure 4-1: Visual depiction of energy calculations, where the energy in the water due to solar water heating = A + B + C

4.2 SWH draw-down tests

Three draw-down tests were performed on the Kuyasa houses, results from which are reported in Appendix 2. However, only data from the most recent test, performed on 5 February 2004, could be used as input and validation to the SWH model since it included (for the first time) solar radiation data for close-coupled systems that was recorded at the same time as the draw-down test itself. The monitoring equipment, which included the solar radiation sensor, was not installed at the time of the first two draw-down tests.

Of the six houses tested at this time, only two of the close-coupled systems did not use hot water during the daytime period between emptying the storage tank and testing hot water volumes and temperatures in the evening, i.e. no draw-offs during the day. Additionally, of these two houses only one, House 56013, had its hot water temperature sensor located in the hot water cylinder itself. The data from this house was thus used in the development of the SWH model³.

4.3 Defining the system efficiencies

4.3.1 Background and literature review

The key unknown in developing the model is the daily heat loss from the system (refer to Appendix 3 for some background information to this problem), which in turn defines the overall system efficiencies. Heat losses occur from the hot water tank, from the heat transfer pipework and from the solar collector itself. These losses vary according to ambient air temperature, wind velocity and hot water usage, and are dynamic in nature.

³ Every effort was made to encourage the residents of the six houses undergoing the draw down test not to use the hot water at all during the day of the test. Had there been greater compliance with this request, a greater sample of houses that met the selection criteria – close-coupled SWH, temperature sensor in the tank – would have resulted. Nevertheless, the fact that one house did meet all the criteria while providing accurate draw off data is considered a sufficient basis for determination of parameters to the model – and Section 4.3 indicates that only one parameter was defined from this data.

The mass flow rate of the water is a key parameter in determining this heat loss factor, and underlies all of the heat losses referred to.

Various approaches to resolving this heat loss issue were attempted. These included defining the overall collector efficiency, modelling the heat loss from the hot water storage tank, modelling the heat loss from the heat transfer pipes, and taking the wind velocity into account. None of these were adequate in predicting the temperatures recorded in the Kuyasa houses.

Since modelling these heat losses is central to the development of a numerically robust model, the first stage of the modelling process involved ascertaining the system efficiency i.e. one which incorporated the heat losses without necessarily specifying them.

A review of efficiencies of SWH systems was undertaken, which included Internet and local technical reports. Christensen & Barker⁴ reported on simulated overall SWH system efficiencies based on hot water demand. Their results are presented in Table 4-1, although the system parameters to which this data refers to is unknown.

Table 4-1: Simulated system efficiencies, from Christensen & Barker (1998)

Hot water demand (litres/day)	System efficiency (%)
150	33,4
225	39,4
300	42,9

In another study, the US Department of Energy's "Energy Efficiency and Renewable Energy" division⁵ indicates that a 3.6 m² thermosyphon close-coupled system, with an annual average hot water drawdown of 243 litres/day, has an annual efficiency of 37%. This is equivalent to a 1.4 m² collector delivering 94.5 litres of hot water per day. This was felt to be appropriate and conservative as a benchmark since the average daily hot water used in each Kuyasa household was 104 litres⁶.

There is clearly also a range in system efficiencies for each SWH, that is dependant on solar radiation, wind, draw-down profiles, etc. The approach taken has been to define the lower and upper system efficiency boundaries, for input to the modelling process.

4.3.2 Defining the lower system efficiency

The lower bound for the system efficiency was calculated using the draw off data. Refer to Appendix 2 for a detailed description of the draw off procedure, and Appendix 4 for the outputs of the process described below. Of the six houses included in the protocol, only one house within these six did not use hot water on the day the draw off test was performed, and met the other criteria for inclusion in the model e.g. that the hot water measurement point was inside the tank. As discussed in Section 4.2, this limited data approach is considered appropriate since the focus here is on model parameter definition as opposed to providing a fully representative sample.

The energy in the water was calculated for each volume of water drawn off and added to the residual heat in the cylinder after the draw off test was complete. During the draw off test the data logger was reprogrammed to save data to the memory every minute (as opposed to the standard fifteen-minute interval). The energy in the drawn off water

⁴ Christensen C and Barker G (1998), *Annual system efficiencies for solar water heating*, Proceedings of 1998 American Solar Energy Society Annual Conference, pp 291 – 296

⁵ http://www.eere.energy.gov/consumerinfo/heatcool/hc_economics_system_savings.html

⁶ Refer to monitoring report 040304.doc

was calculated as the sum of the energies in each drawn off water volume that was recorded on the data logger. The equation (Equation (1)) used is:

$$\sum (\text{mass of the water (assumed equal to the volume)}) * (\text{the specific heat capacity of water (4.187 kJ/kg.}^{\circ}\text{C)}) / (3600 (\text{kJ to kWh conversion})) * (\text{hot water temperature} - \text{cold water inlet temperature})^7.$$

Equation (1) totals 2.17 kWh, over a total draw off volume of 166 litres.

The residual energy in the hot water storage tank was calculated as (Equation (2)):

$$100 \text{ litres} * (\text{the specific heat capacity of water (4.187 kJ/kg.}^{\circ}\text{C)}) / (3600 (\text{kJ to kWh conversion})) * (28.8 (\text{hot water temperature at end of test}) - 25.0 (\text{cold water inlet temperature at end of test})).$$

Equation (2) totals 0.44 kWh.

The total energy in the hot water is the sum of Equation (1) and (2), equalling 2.61 kWh.

The measured solar radiation incident on the 1.4 m² collector between the emptying of the cylinder at the start of the draw off test and the final water volume drawn off was measured to be 7.08 kWh.

Thus, the overall system efficiency was determined to be 2.61/7.08*100 = 36.9%. Since a once-off total draw off of water is the most inefficient use of the solar water heater, this figure was set as the lower bound of the system efficiency range.

4.3.3 Defining the upper system efficiency

A statistical approach was taken in then determining the upper bound for the system efficiencies. The recorded data for the four houses was used to calculate each system's actual daily average performance, based on the above formulae and using the measured hot water consumption (see Section 3).

Knowing the minimum system efficiency (36.9%), the above set of data reflecting the daily system efficiency for each of the four houses was reduced to include only those efficiencies that were greater than this minimum figure. The resulting data set, which ranged in population from 17 to 81 days, provided a logical framework for statistical processing to calculate the maximum system efficiency - which by definition would have to be greater than the calculated 36.9% minimum.

The results of the statistical processing of this data set are reflected in Table 4-2 below. The resulting confidence intervals for each house were assessed, with the lowest possible system efficiency selected as the upper bound of the system efficiencies. The figure of 42.2%, selected from House 56013, was selected as this maximum system efficiency and will ensure that the most conservative model output is achieved.

Table 4-2: Confidence intervals on upper bound of system efficiencies

House number		56013	54610	55747	56586
Inputs	means	0.50	0.57	0.61	0.63
	standard deviations	0.150	0.235	0.246	0.371
	n	17	81	19	43
	confidence level	0.95	0.95	0.95	0.95
Outputs	t-percentile	2.12	1.99	2.10	2.02
	standard error	0.036	0.026	0.057	0.057
	Half width	0.077	0.052	0.119	0.114

⁷ This is the classic heat flow equation: $Q = \sum(m.c.\delta T)$. Refer here to Appendix 3.

Confidence interval	Lower bound	42.2%	52.1%	49.0%	52.0%
	Upper bound	57.6%	62.5%	72.8%	74.8%

4.4 Model calculations and outputs

Table 4-3 summarises the inputs to the SWH models for each of the four houses:

Table 4-3: Input parameters and their characteristics

Input parameters	Source	Frequency	Value (unit)
<i>Cold water temperature</i>	Measured	Daily	Variable
<i>Collector area</i>	Manufacturer	n/a	1.4 (m ²)
<i>Horizontal solar radiation on collector</i>	Calculated	Daily	Variable (kWh/day)
<i>Tilt conversion factor from SOLATILT</i>	Calculated	Monthly	Variable (none)
<i>Azimuth angle (θ)</i>	Measured	n/a	Variable (degrees)
<i>Azimuth conversion factor</i>	Calculated	Yearly	Variable (none)
<i>Hot water temp in cylinder</i>	Measured	Daily	Variable (degrees)
<i>Storage tank volume</i>	Manufacturer	n/a	100 (litres)
<i>Overall system efficiency</i>	Calculated	Yearly	Variable (none)
<i>Specific heat capacity of water</i>	Constant	n/a	4.187 (kJ/degC/litre)
<i>Energy conversion factor</i>	Constant	n/a	3.6 (kWh/MJ)

In determining the effective amount of solar radiation striking the solar collector on each solar water heater, the tilt and azimuth angles of each had to be taken into account. These angles refer to deviation from the horizontal and from true north, respectively. The tilt angle on the four houses' SWHs is 25 degrees, while the azimuth orientation of each house is presented in Table 4-4:

Table 4-4: House azimuths

House #	Azimuth
56013	52 ^o , east of true north
54610	49 ^o , east of true north
55747	44 ^o , east of true north
56586	34 ^o , east of true north

The azimuth correction was approximated by using the cosine of the azimuth angle, raised to the power of 0.3 - this approach is detailed in Appendix 4. The measured data for the four houses was used to calculate each system's daily performance. For each day, the energy calculated to be in the water (using average hot water demand, and cold and hot water temperatures) was divided by the effective solar radiation on the SWH collector. The effective solar radiation is the product of the measured solar radiation multiplied, the tilt correction factor and the azimuth correction factor.

The model then calculates the energy in the drawn off water, with the following approach:

- If the daily calculated efficiency $\eta < 36.9\%$, set $\eta = 36.9\%$
- If $\eta > 42.2\%$, set $\eta = 42.2\%$
- Otherwise, leave η as calculated.

Thus, low calculated daily system efficiencies are corrected by allowing the model to incorporate any residual solar heat that might otherwise reside in the water but that might not have been fully captured in low water volumes being drawn off. Similarly, excessively high daily system efficiencies corresponding to days of low solar radiation but high draw-offs (with residual heat carry-over, perhaps) are corrected to correspond to the calculated maximum possible efficiency.

The final output of the model for each house was corrected to adjust for a year's solar radiation. The average daily horizontal radiation for the period was compared with the historic average daily horizontal radiation data for Cape Town⁸. The former was measured as being 5.43 kWh/day, while the latter is 5.27 kWh/day.

The results were thus multiplied by $(365/\text{PERIOD}) \times (5.27/5.43)$ in order to extrapolate the results to give annual energy equivalents.

Additional details of the model development and validation process are provided in Appendix 4.

5. Results

In total there are four houses with a close-coupled SWH that fit the criteria for input to the model. Results from the model for these houses are presented here, with averaged results for each house presented in Table 5-1.

Table 5-1: SWH model results: solar energy in the water

House #	Azimuth (degrees)	Period (days)	Average solar energy transferred to SWH per day (kWh)	Average solar energy transferred to SWH over period (kWh)	Average solar energy transferred to SWH per annum (kWh)
56013	52	129	2.58	333.3	915.2
54610	49	145	2.55	370.4	904.8
55747	44	145	2.50	362.4	885.5
56586	34	145	2.67	386.7	944.7
AVERAGE	44.8	141	2.58	363.2	912.5

These results indicate that, on average, each SWH that is oriented between 34 and 52 degrees in an easterly direction from true north, with a tilt angle of 25 degrees from the horizontal, and with random daily hot water demands, captures 912.5 kWh of solar energy per annum.

6. Conclusions

This model has been used to predict the volumes of hot water delivered by a SWH system. The average solar contribution to available hot water for a SWH is calculated to be 912.5 kWh per annum. At all times where a choice of parameters could be made, the most conservative one has been selected. In addition the result is conservative since the four houses used for input to the model have an azimuth orientation of between 34 and 52 degrees in an easterly direction, which will result in a much lower quantity of energy being transferred to the water were they to be oriented in a more northerly direction.

⁸ Cowan WD et al (1992). RAPS Design Manual: Vol. 2, Energy for Development Research Centre, University of Cape Town. This information is taken from data presented in the SOLATILT program – see also Appendix 4 where the average solar radiation at 0 degrees (i.e. horizontal) is 5,268 W/day

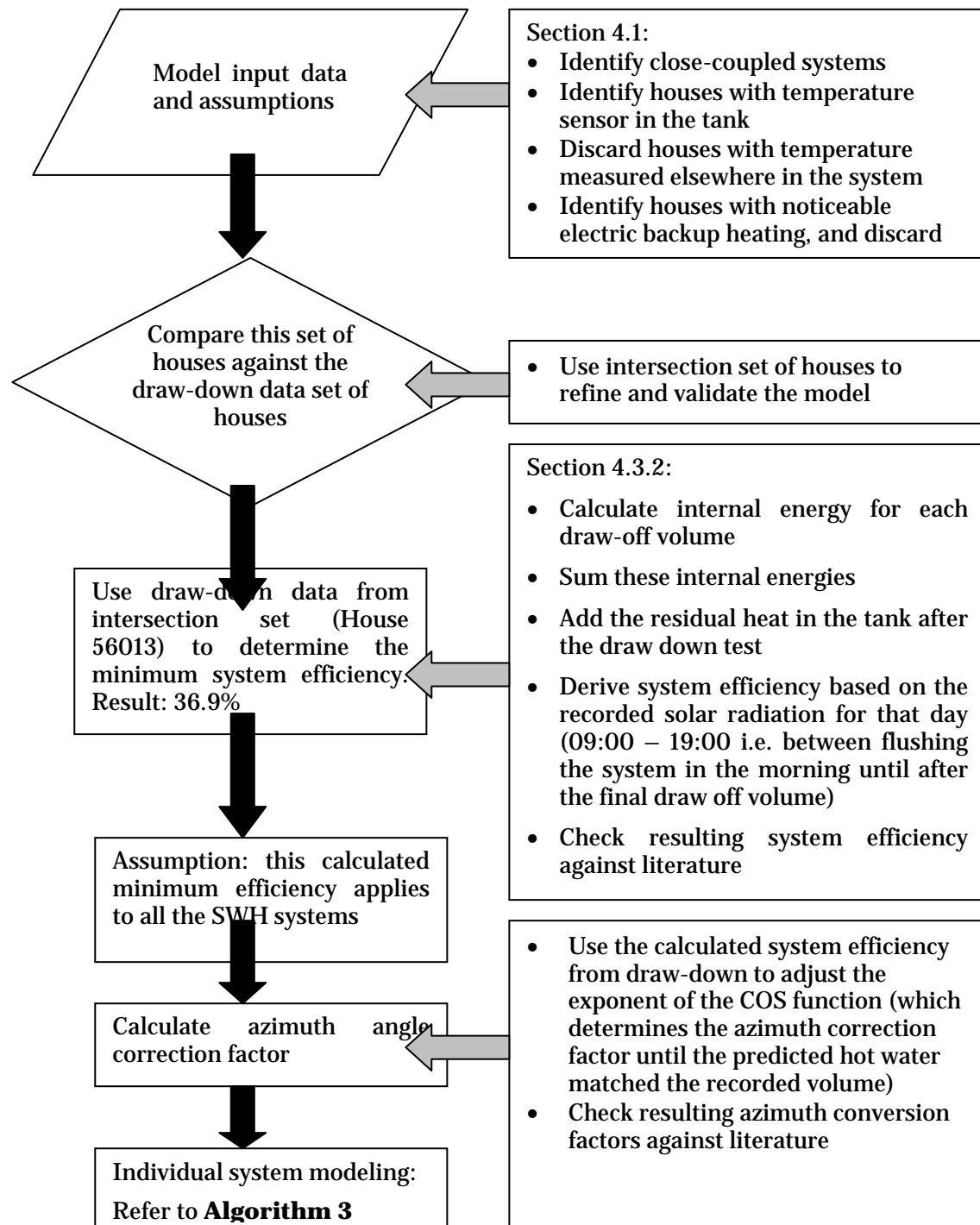
Given the poor orientation of these SWH systems, all efforts should be made in the future project activity to ensure that the SWHs are orientated in a more northerly direction.

The combination of the various input parameters does not allow for any trends to be identified with regard to system performance against any one parameter. On average, though, each house saves the household at least 900 kWh for water heating per annum.

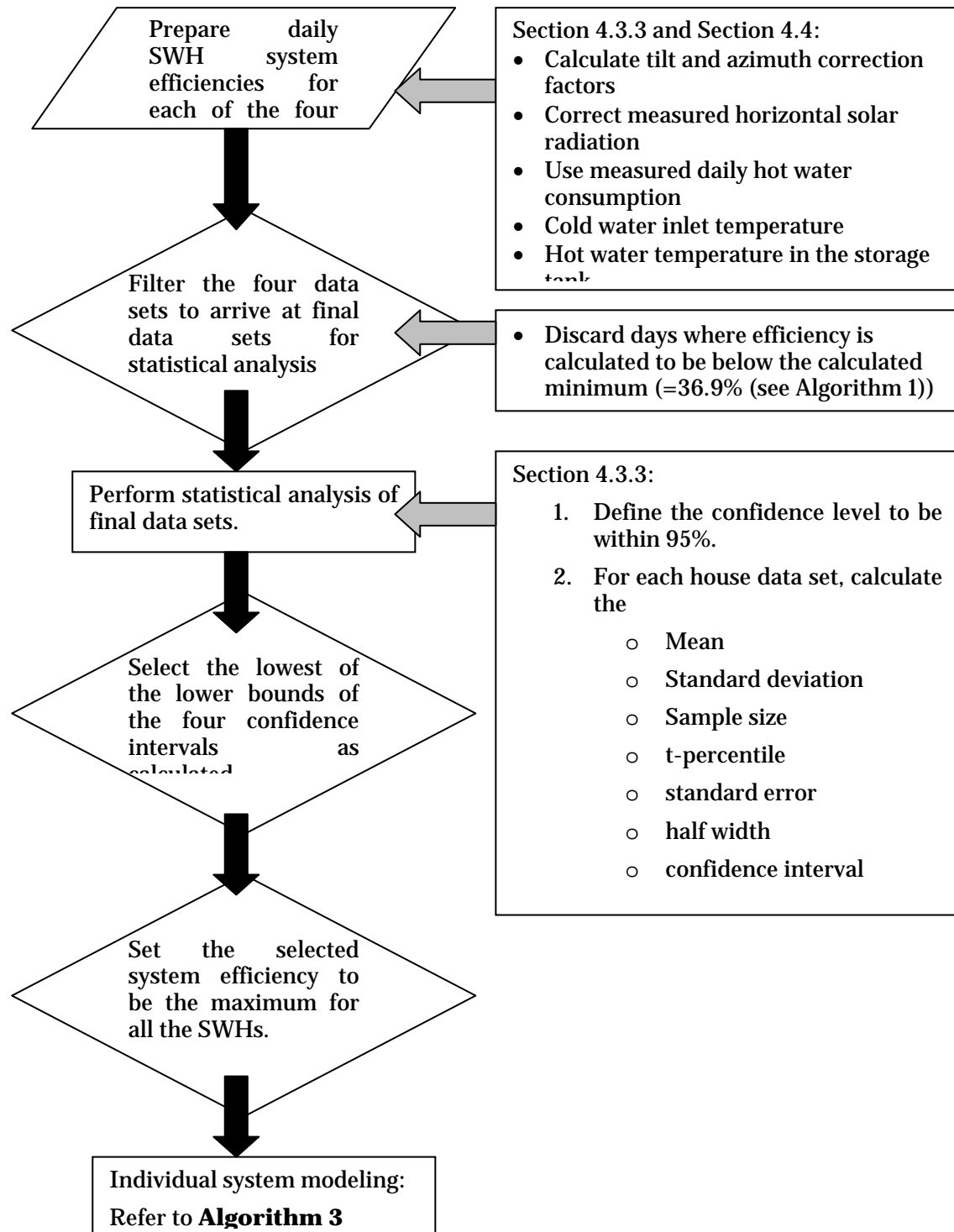
This model and resulting data can be used to determine the avoided carbon dioxide emissions resulting from the coal-fired generation of electricity used to heat water in standard hot water storage geysers taking into account transmission and distribution losses and standing losses.

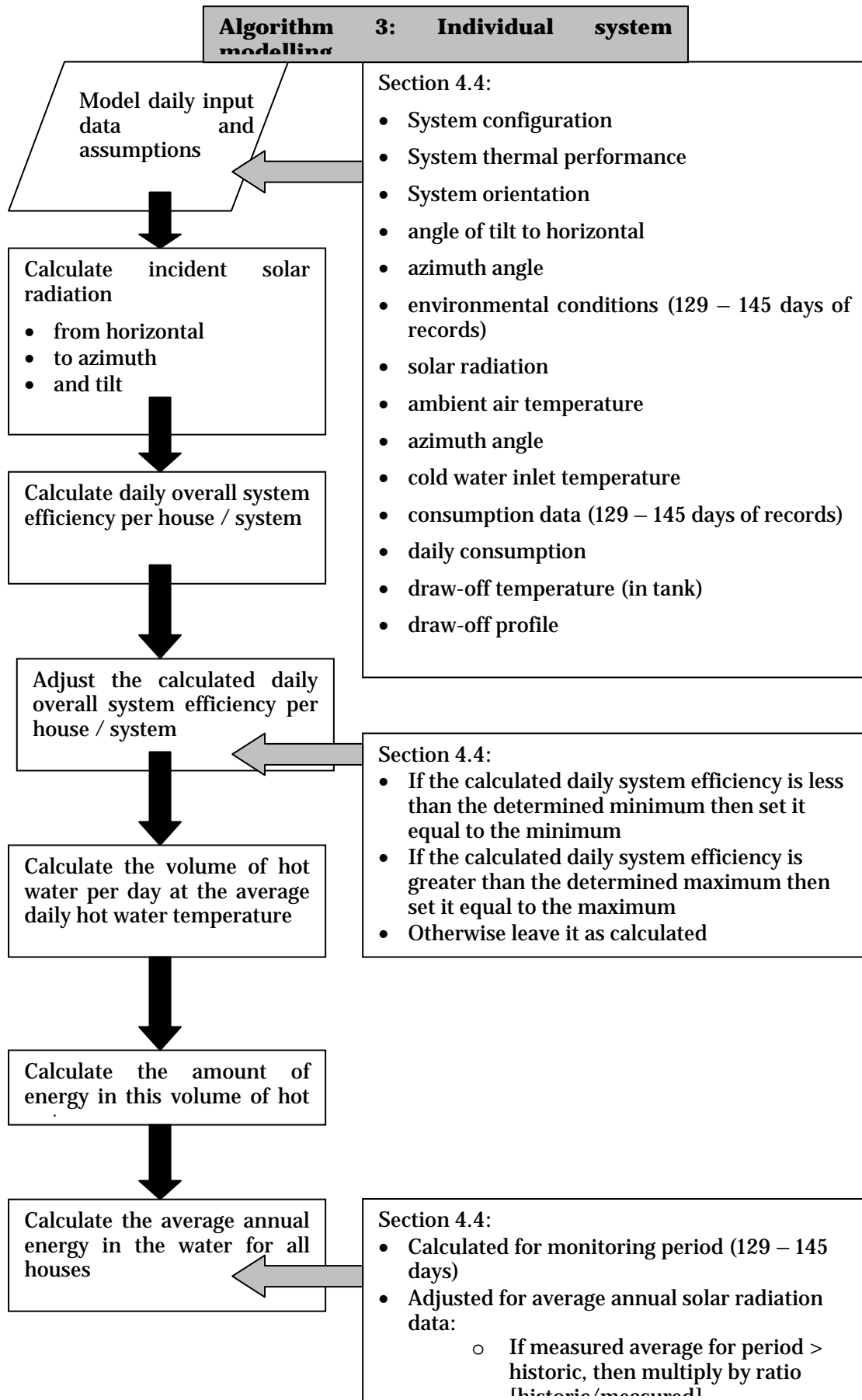
1. Appendix 1: The modelling algorithms

Algorithm 1: Data set definition and minimum SWH system efficiency



Algorithm 2: Determining the maximum SWH system efficiency





2. Appendix 2: SWH draw-down tests

Background

AGAMA Energy (Pty) Ltd was contracted by SouthSouthNorth to provide technical support for the Kuyasa Low-income housing project. The Kuyasa Project is a Clean Development Mechanism (CDM) demonstration project, aimed at promoting energy efficiency within low cost houses. AGAMA Energy designed and project managed the installation of three energy efficient interventions comprising the scope of the project, namely hot water on tap supplied by solar water heaters (SWHs), enhanced indoor comfort levels by means of thermal insulation (insulated ceilings) and more energy efficient lighting using compact fluorescent light bulbs (CFLs).

The overall scope of the project included the monitoring of all three interventions for a period of six months and, more specifically, to develop a model that will simulate performance for large scale SWH systems. The main objectives of tests were to:

- determine the performance of the installed SWH systems
- provide some basis for validating the SWH model

Although data logging systems were installed to capture the usage of hot water in the houses, as well as other information related to the performance of the systems, manual draw down tests were also conducted by AGAMA Energy representatives and again by the beneficiary's representatives under supervision of AGAMA Energy. Tests were conducted in different stages of the project, after installation and again after six months of operation.

This report describes the methodology and performance of the three drawdown test that were performed on houses in Kuyasa.

Objectives

The main objective of the test was to measure the performances of the different SWH systems installed to determine the amount of useable hot water (water at a specific temperature) that the systems can provide in a clear day. Knowing the solar radiation in the area, which was also measured in one of the houses, the results obtained could be used to validate a numerical model developed to determine the amount of useable hot water from SWHs with different orientations.

The other objectives for these activities were to assure the beneficiaries and the manufacturers that the systems work and to transfer technical knowledge of SWH performance to the beneficiaries and assistants involved with the tests.

Scope of the activities

The installed data logging systems do not necessarily provide conclusive determination of the SWH system performance. Due to logistical constraints the drawdown tests could not be conducted on all the houses at the same time. Instead, three drawdown tests were planned with one, five and six houses tested each time respectively.

The ten houses had three different makes of SWHs installed: eight were of the close-coupled type, and two were integral units. Of the close-coupled units, four each were supplied by Solar Dome and Atlantic Solar, while the two integrals were supplied by Solar Beam. All three makes have a 100-litre water storage volume, and the close-coupled units have a 1.4 m² collector.

The first drawdown test was conducted by all beneficiaries' representatives on an integral system on house 56290 as a learning exercise. No particular selection criterion was used to test the SWH on this house except that it was easily accessible by all assistants.

The second drawdown test was conducted on 10th September 2003 on houses that were selected on the basis of their location and SWH system type. They are concentrated in one area - generally considered to be the 'inland' part of Kuyasa - with four closed coupled systems and one integral system, on houses 54424, 55580, 54610, 54979 and 54516 respectively.

The last test was conducted on 5th February 2004 on the remaining 5 houses from the opposite - the 'sea' side - area. These were houses 56139, 56586, 55747, 56013 and 56290. Also, in order to compare the performance of the close coupled systems installed by two different manufacturers, house 54424 was included to make up the sixth SWH to be tested. This house was selected since its orientation closely matched that of house 56139 in being close to true North.

Participants

For the first test, the beneficiary's representatives were divided into groups of three since it was a training exercise. Five participants associated with the houses selected for the second drawdown test conducted their house tests under AGAMA Energy's supervision.

Following the results from the second drawdown, from which some results were not satisfactory, the last test was conducted by AGAMA Energy representatives and one project steering committee member. The first house was done by all people together, while the remainder were performed by groups of at least two people working together.

Methodology

Despite the accuracy of the instruments utilized, reliability of any test conducted is a function of the method and procedure followed before or when the test was conducted.

Instrumentation

A drawdown test does not necessarily need the most accurate and precise instrumentation; instead the most commonly required tool is a thermometer for measuring water temperature. In the test mercury and alcohol thermometers were used as shown in Figure 6-1 below. The only other equipment required is a 5-litre bucket, and pencils and paper.

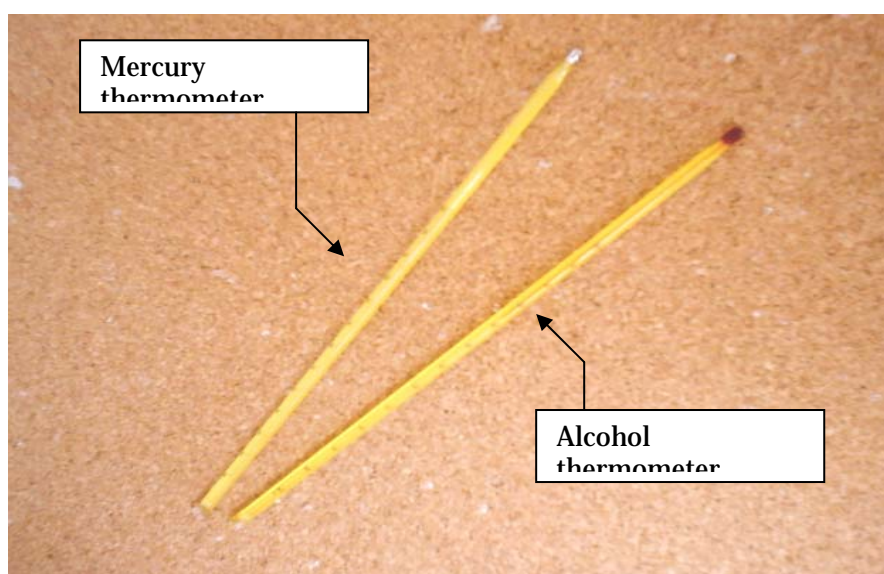


Figure 6-1: 110 °C Mercury and Alcohol thermometers

Test Procedure (Method)

The information provided here is limited to the third and last drawdown test only, since it is the only test performed at the same time that the solar radiation was being measured, thus allowing the results to be integrated in the SWH model. Before the SWH test is conducted, there are certain procedures that need to be undertaken, while the weather also needs to have been confirmed to be clear on the day of the test in order to achieve the best results.

In all tests conducted, the weather was confirmed clear from the South African Weather Bureau some days before the test. Household members were informed of the day and requested not to use hot water from the system since that would reduce the accuracy of the test.

The test was originally scheduled for Tuesday 3rd February 2004, but was postponed for weather reasons to Thursday the 5th February. In the early morning on the day of the test, an AGAMA Energy representative accompanied by one of the steering committee members emptied all the tanks of the systems that were to be tested, and programmed the data logging system to record every minute. At the same time all the beneficiary's household members available were again requested not to use any hot water from their SWH for that day until after the test was conducted that evening.

Manual drawdown test

The manual test on 56290 was conducted using 2 thermometers, since these results are presented in Appendix A. A test team comprising two people conducted the manual drawdown test with one taking water from the tap and the other taking the temperature reading and recording it. Some of the parameters recorded in the test proforma document (see PDD attachment J) are the name of the person conducting the test, house number, date, time ambient temperature and the duration of the test. Assistants were also asked to record any general observations.

The procedure, of drawing hot water from the interior tap at 5-litre volumes, was repeated at least thirty times, resulting in at least 150 litres of water being drawn out of the 100 litre tank. Theoretically the procedure is repeated until the water coming out of the system is at the same temperature as the municipal water however that could take a long time, and be an unnecessary waste of water. See Appendix A for results of the manual download.

Automatic drawdown test

The automatic drawdown is the data recorded by means of the electronic data logging system. The accuracy of the test is highly dependent on the logging interval set in the data logger. In this instance the datalogger was set to record the amount of water drawn and the temperature from the system every minute. The logger digitally recorded all the information, which was later downloaded to a laptop at the end of the test.

Findings

Data analysis

A total of 30, 5-litre buckets were drawn from each system, giving 150 litres total amount of water drawn from each house. Despite the request of all households not to use water, the results from the data loggers showed that only two of the six households did not use their hot water during the day of the test. In addition it was noted that house 55747 not only used water but also had their electric backup heating element switched on during the day of the test, and thus the results will be excluded from analysis in this report. Table 6-1 shows total amount of water used per house during the day.

Table 6-1: Water usage by house on the day of the test

House #	54424	56290	56139	56013	56586	55747
Water used during the day in litres	29	15	0	0	66	25

Quality of data

A total of 30 good records were recorded manually from each house (refer to Appendix A).

Since the main purpose of the drawdown test was to validate the SWH model, the use of water by four houses during the day of the test renders the test data from these houses not useful for that purpose. Though they still provide qualitative data about the performance of the SWH systems, they are inconclusive about the absolute volume of hot water produced. Thus, the data from houses 56139 and 56013 is the only data acceptable in order to validate the SWH model.

Due to delays in performing the tests, some tests were conducted late when the sun was no longer shining. It can be assumed therefore that these systems could have lost some of the heat to the environment. The results are consequently more conservative.

Solar radiation data for the last three days including the drawdown test day was found to be dubious, with the radiation sensor suspected to be malfunctioning. This was concluded after the data for the day was downloaded and found to be almost triple the magnitude of average irradiation for the day. The fault was backtracked and found that it started when the logger was changed to a 15-minute logging interval before to a minute for the download period.

Furthermore, Cape Town is a coastal region that experiences windy days. One limitation of the data obtained is that the cooling effect of the wind cannot be disaggregated from the results, which could lead to differing performances for the otherwise same set of climatic parameters with different wind speeds. It should be noted that the most recent drawdown test, which was used for the model development and validation, was undertaken on a relatively windy day. The results are thus expected to be conservative in terms of understanding the general performance of the SWHs.

Drawdown test results

All houses

All the drawdown test results are presented graphically in Appendix B. Water usage during the day of the test has an enormous effect on the volumes of hot water measured during the drawdown test. As shown in Table 6-1 above, house 56586 used the largest amount of water during the day, and hence its hot water temperature profile is the lowest of all six houses in Appendix B.

Close-coupled systems

House 56013

The ambient and cold water temperatures during the time of test on house 56013 were 26°C and 25°C (average) respectively (refer to Appendix A). The maximum hot water temperature recorded from the system is 52°C at the tap. However on analysis this system was able to provide an amount of 44 litres of hot water (water above 40°C) based on the datalogger data, and 60 litres based on the manual measurements. Figure 6-2 below shows the drawdown test temperature profile, layout and characteristics for house 56013.

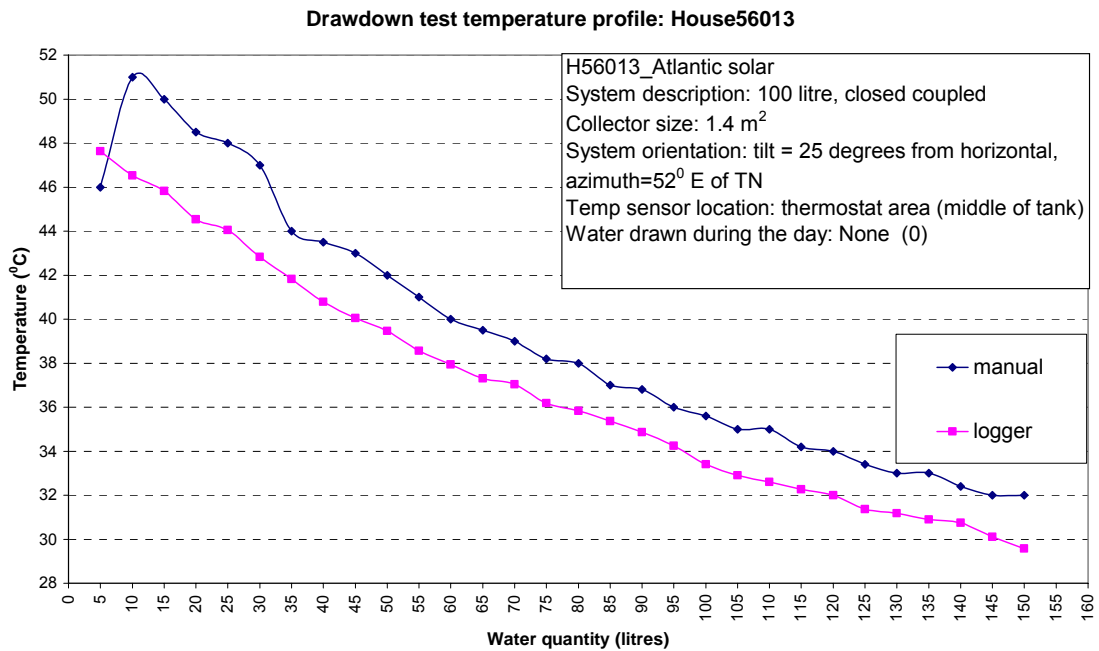


Figure 6-2: Drawdown test profile for House 56013

Referring to Figure 6-2, the manual temperature profile is hotter than the logger profile. This difference is primarily due to the vertical position of the electronic sensor, which in this instance is located in the thermometer housing, about two-thirds of the way up the side of the tank. Thus the maximum water temperature, which would occur at the top of the tank, is not being measured. Secondly, because this sensor is not measuring the water temperature directly one would expect a degree of heat loss from this housing to the environment.

Consequently, the useable water volume of 60 litres is the more accurate reflection of the thermal performance of the system.

House 56139

The cold water temperature was measured as being 24°C. Maximum hot water temperature measured (manually) at the tap was recorded at 49.5°C. Overall, house 56139’s SWH system is able to supply 102 litres of hot water at more than 40°C at the tap in a clear day, based on the electronic data, and 100 litres (at over 40°C) using the manual temperature data. The SWH system of this house is one that is properly orientated, at about 5 degrees from True North. The graph of both the manual and logger profiles with the characteristics and layout of the system are shown in Figure 6-3.

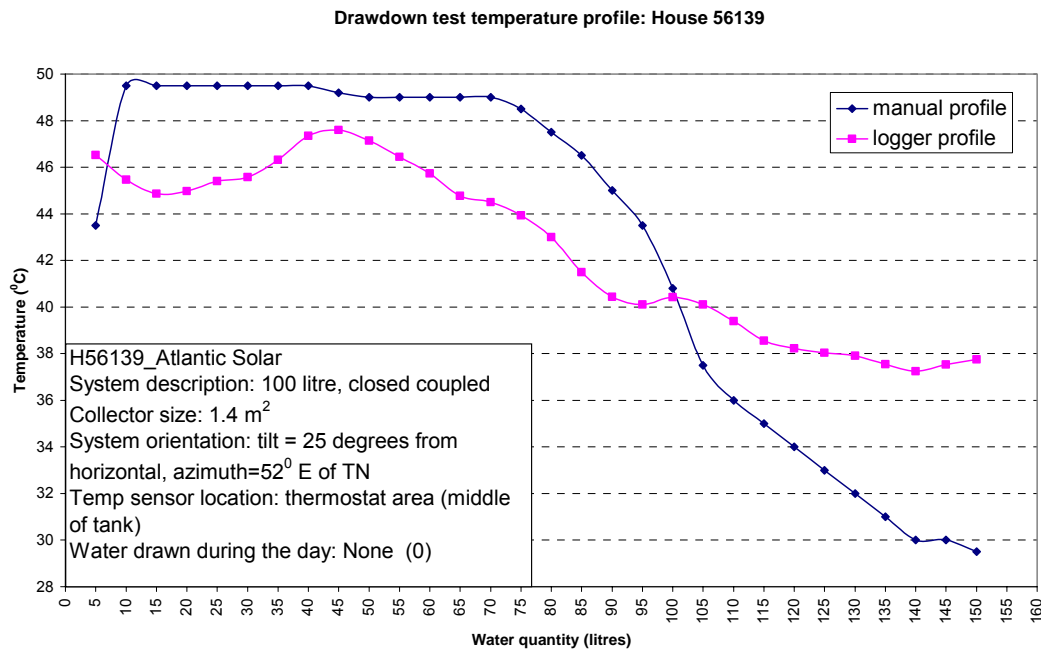


Figure 6-3: Drawdown test profile for House 56139

Figure 6-3 shows some similar characteristics to Figure 6-2 above, except that after 100 litres of hot water was drawn out of the system, the logger profile for house 56139 remains higher than that measured at the tap. This is primarily due to the temperature sensor of house 56139 being located on the outlet pipe of the solar tank, by means of an insulated strapping around the pipe. Since the sensor is not in direct contact with water, the temperature measured is that of the pipe itself, in turn receiving heat by conduction from the water within.

The copper pipe has the effect of reducing the peak temperatures registered by the sensor, while also delaying the transmission of the actual temperature to the sensor. This effect creates a low temperature drop or more gradual temperature change measured by the logger sensor.

Integral systems

The draw-down test on 5th February 2004 did not include either of the two integral SWH systems which were installed in Kuyasa. A typical draw-down profile for the integral SWH systems is shown in Figure 6-4. This draw-down profile was based on manual measurements which were recorded as part of the commissioning procedure for the systems.

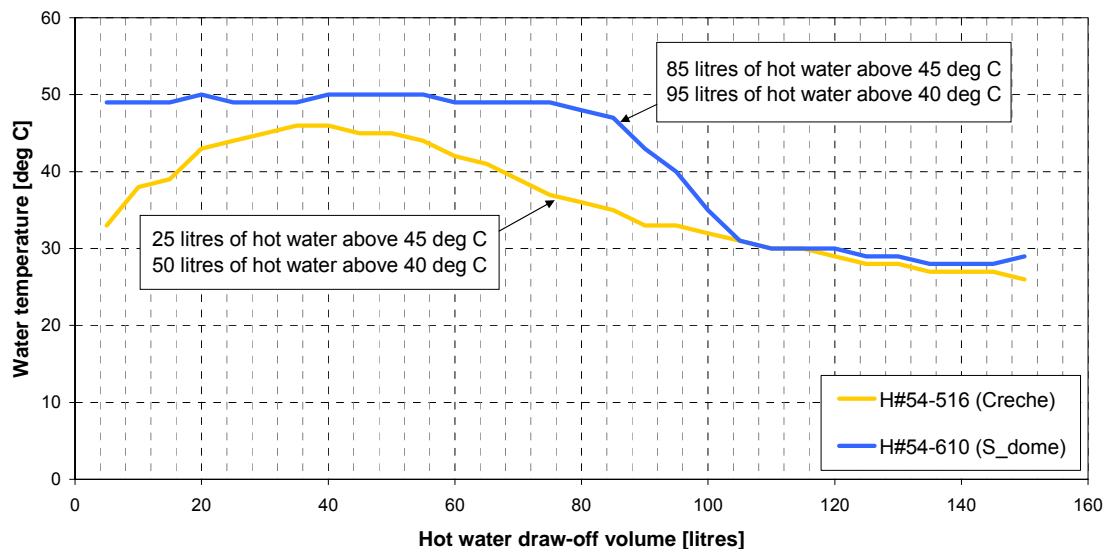


Figure 6-4: Draw-down test for an integral SWH system (on the Crèche)

This profile shows water at the tap coming out at approximately 33°C. This is due to the initial configuration of the 25 litre electrical storage backup water heating cylinder which was installed directly in-line with the SWH system. Consequently, as shown, the cold water in this inline backup heater had to be drawn off before the solar heated water became available. This configuration was changed as a consequence and now hot water is supplied either from the integral SWH system directly or, alternatively, directly from the backup water heater.

As shown, the 55 litre integral SWH system delivered 50 litres of hot water at more than 40°C despite the less-effective configuration.

Discussion

As discussed above the data from all houses that used water during the day of the test are considered invalid for the purpose of this report and therefore will not be discussed.

Using the data logger information, house 56013 and 56139 SWH heating systems were able to produce 44 litres and 102 litres of water above 40 °C respectively. Using the manual drawdown information, house 56013 and 56139 SWH heating systems were able to produce 60 litres and 100 litres of water above 40°C respectively.

There is a significant difference between the two systems' performances which is primarily associated with their orientation. Clearly, the SWH on house 56013 is under performing due primarily to the fact that it is facing 55° off True North.

Conclusion

Despite the water usage on some of the houses during the day of the test, the test was conducted successfully and the results as expected were acceptable. The result shows that the installed SWH are in good working condition, however performing significantly differently as a result of their varying orientations from true North. As expected the SWH system which is orientated nearer true North performs better than the one which is facing away from true North.

Recommendations

In order to improve the results from the next SWH drawdown tests conducted on installed SWHs in the future, the following recommendations are made:

- Before any SWH draw-down test is conducted, a strategy should be devised to ensure no water is utilised during the day.
- Draw-down staff need to have ensured access to the house for the duration of the day of the test.
- SWH systems' collectors should be cleaned in order to remove sand and dust a day or two before the test.

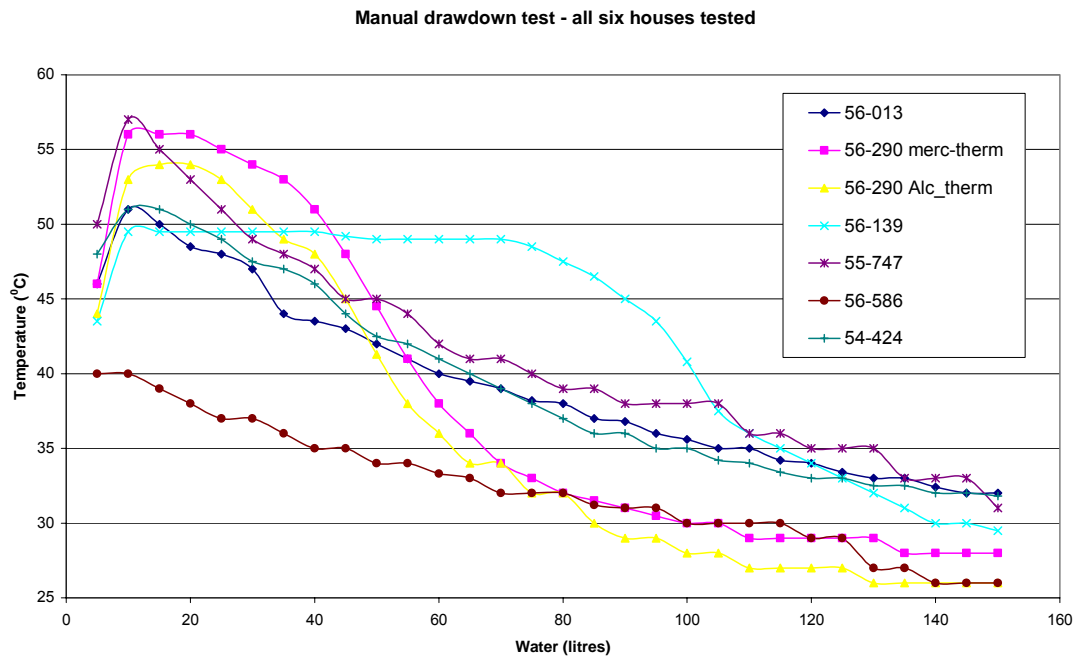
Finally, it is highly recommended that on both the second phase of the Kuyasa Project and on any other installation of SWH systems that they are oriented as near to true North as possible.

Appendix A: Manual drawdown data

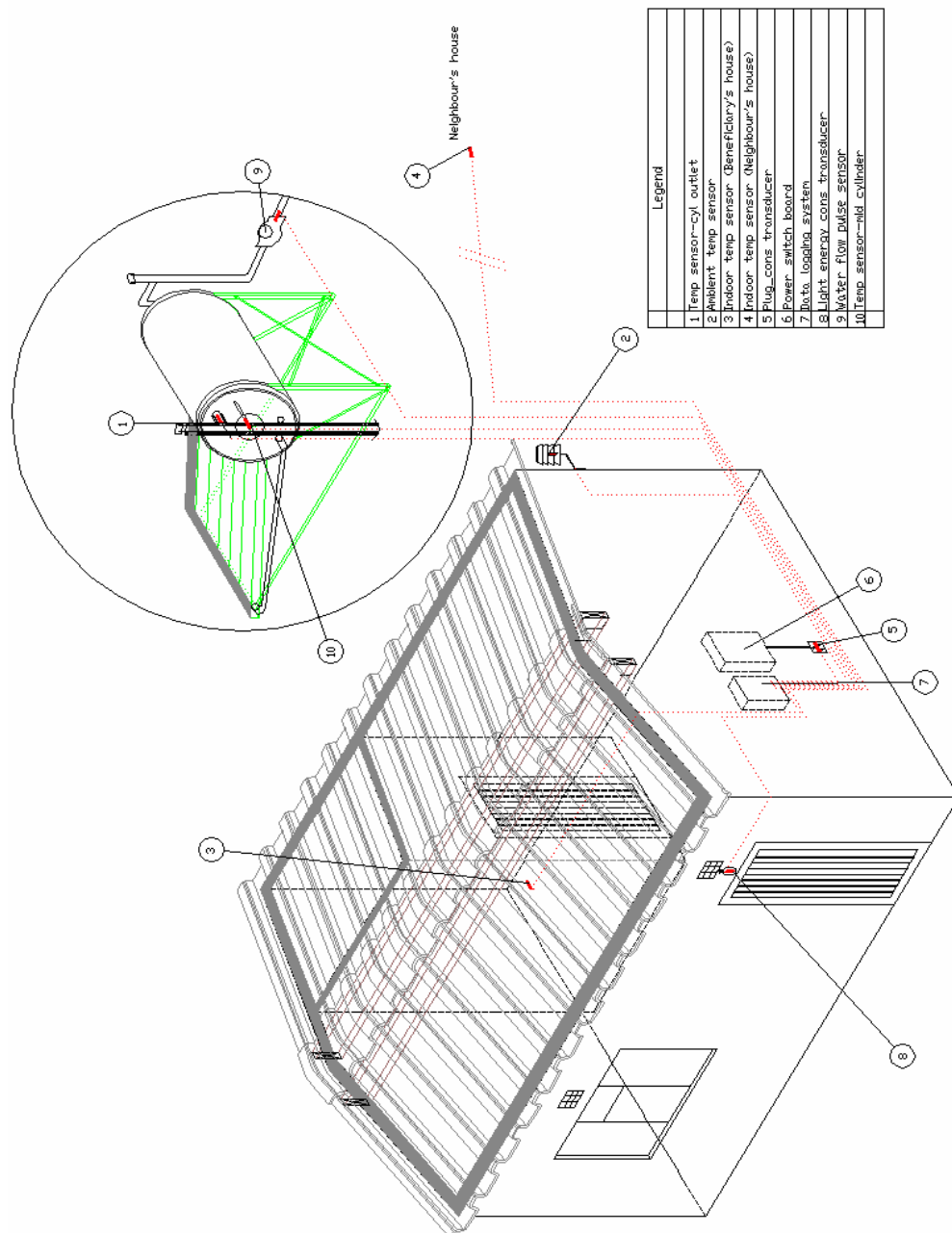
Date: 05 February 2003

	Start time:	17:15	17:15	17:15	17:00	19:24	18:10	19:35	
	End time:	18:07	18:07	18:07	17:40	20:10	18:50	20:11	
	Ambient temp	26	27	27	25.5	23	24	24	
			Manual Drawdown test						
		AT-sol	Sol-HD	Sol-HD	AT-sol	AT-sol	AT-sol	SOL-dom	
House #		56013	56290	56290	56139	55747	56586	54424	
Water drawn (litres)	Temp #		Mercury therm.	Alcohol Therm.					
5	1	46	46	44	43.5	50	40	48	
10	2	51	56	53	49.5	57	40	51	
15	3	50	56	54	49.5	55	39	51	
20	4	48.5	56	54	49.5	53	38	50	
25	5	48	55	53	49.5	51	37	49	
30	6	47	54	51	49.5	49	37	47.5	
35	7	44	53	49	49.5	48	36	47	
40	8	43.5	51	48	49.5	47	35	46	
45	9	43	48	45	49.2	45	35	44	
50	10	42	44.5	41.3	49	45	34	42.5	
55	11	41	41	38	49	44	34	42	
60	12	40	38	36	49	42	33.3	41	
65	13	39.5	36	34	49	41	33	40	
70	14	39	34	34	49	41	32	39	
75	15	38.2	33	32	48.5	40	32	38	
80	16	38	32	32	47.5	39	32	37	
85	17	37	31.5	30	46.5	39	31.2	36	
90	18	36.8	31	29	45	38	31	36	
95	19	36	30.5	29	43.5	38	31	35	
100	20	35.6	30	28	40.8	38	30	35	
105	21	35	30	28	37.5	38	30	34.2	
110	22	35	29	27	36	36	30	34	
115	23	34.2	29	27	35	36	30	33.4	
120	24	34	29	27	34	35	29	33	
125	25	33.4	29	27	33	35	29	33	
130	26	33	29	26	32	35	27	32.5	
135	27	33	28	26	31	33	27	32.5	
140	28	32.4	28	26	30	33	26	32	
145	29	32	28	26	30	33	26	32	
150	30	32	28	26	29.5	31	26	31.8	

Appendix B: Drawdown test data for all houses



Appendix C: Layout of the data logging system and sensor locations.



3. Appendix 3: Description of solar water heaters

Typically, SWHs fit into two broad categories: close-coupled, and integral, units. The Kuyasa study involved installing eight close-coupled units as well as two integral units. The close-coupled unit has three parts: the absorber, the energy transfer loops, and a storage tank, whereas an integral unit has one component, being an absorber with a sufficient volume that doubles as the hot water storage. The close-coupled units are more efficient than the integral type, while costing up to four times the initial cost price. We focus here on the close-coupled units.

The interaction of the three components making up the close-coupled SWH is so complicated that a perfect mathematical model of the system has not yet been developed. By making assumptions expressions can be derived that simulate the function of the system.

The absorber has three purposes:

- to transform as much as possible of the available solar radiation into heat,
- to minimize losses, and
- to transfer as much as possible of the heat collected into the thermal storage cylinder.

Solar radiation striking the blackened absorber plate is converted to heat and is conducted along the absorber sheet to the water tubes. The water flowing through the tubes is therefore heated and so energy is fed to the heat transfer loop and into the thermal storage tank.

The radiation exchange characteristics of the absorber plate have an important bearing on the thermal performance of the collector. The ability of the absorber plate to convert solar radiation into heat is measured by its absorptance. On the other hand, the plate loses heat both by convection and radiation, and to a small extent by conduction. Convection losses are reduced by fitting one or more transparent cover sheets and sealing the absorber box, and radiation losses can be reduced by treating the surface of the absorber plate to make it a selective absorber of radiation. A non-selective surface, such as might be produced with a suitable matt black paint, might have an absorptance of 0.95, but its emittance would also be 0.95. This means that the amount of energy that it loses by radiation is 95% of what a black body would lose at the same temperature.

However, simple processes have been developed to treat copper sheets and produce selective surfaces for which absorptance = 0.90 and emittance = 0.15. Although they absorb slightly less than the non-selective surface, they reradiate a lot less, and are worthwhile for collection temperatures exceeding about 20 degrees Celsius above ambient.

The incident radiation

The solar energy incident on a plate absorber is at a maximum when its plane is normal to the incident radiation. However, it is not very practicable to mount absorbers in small systems in such a way that they follow the Sun's movement, since this would require rotation about two axes to allow for both daily and seasonal changes in the Sun's position. The complication and cost of such an arrangement are such that generally it is cheaper to increase the area of fixed absorbers rather than install sun-tracking mountings.

The angle of inclination of an absorber should be related to the latitude of the location. The maximum amount of energy incident on a fixed surface facing north occurs when the inclination to the horizontal is about 0.9 times the latitude. This is not very critical, and it depends on how much of the radiation is direct and how much diffuse. This factor is

therefore an important consideration in the design of systems and components, and is one reason why plate absorbers are superior to concentrating collectors, which can use only the direct component of the radiation.

Most solar radiation recording stations measure only the global radiation incident on a horizontal surface, that is, total direct and diffuse radiation coming from all parts of the sky. Accordingly, we would like to be able to predict from these readings the insolation on a surface at any inclination and orientation, but the methods which have so far been developed are not very accurate. If we want to know the amount of solar radiation incident on a surface at some unusual angle of inclination and orientation to better than about 10% it has to be measured.

Plate absorbers and their heat loss

In order to be able to simulate solar water heating installations on a radiational basis we must be able to predict the performance of an absorber for the conditions under which it will operate. The useful energy output from the absorber to the heat transfer loop at any instant is the product of the mass flow rate of the fluid, its specific heat, and its temperature rise (see Equation (1) below).

A flat plate absorber is a very complex thermal system, and there are many expressions in the literature which have been developed over the last thirty years to enable these losses to be calculated. These are valuable in developing and designing absorbers as components of heating systems, but simplified expressions are necessary for normal design and simulation purposes. To this extent, there are now many simulation software packages available, the most extensive, and popular, being TRNSYS, which is a modular program that is almost infinitely adaptable.

In a flat plate absorber the useful heat collected H is equal to the incident solar radiation G minus the losses L . The losses are of two kinds:

- losses which reduce the amount of incident solar radiation striking, and being absorbed by, the absorber plate; and
- losses from the plate after the solar radiation has been converted into heat.

This useful heat H is expressed by,

$$H = A_r * G - U(T_{wm} - T_a) \quad (1)$$

where A_r is the radiation absorbing coefficient of the absorber,

G is the insolation on the plane of the absorber,

U is the absorber heat loss coefficient,

T_{wm} is the mean water temperature in the absorber,

T_a the ambient temperature.

The constants A_r and U are characteristics of an absorber and completely define its performance at the operating temperature T_{wm} , insolation G , and ambient temperature T_a and wind velocity V . To obtain the daily or annual heat collected, Equation (1) must be integrated over the time period concerned. For design calculations, particularly involving computer simulation, it is more convenient to write Equation (1) as a differential equation

$$\partial Q = A_r * \partial I - U(T_{wm} - T_a) \partial t \quad (2)$$

where δQ (Joules) is the incremental heat input from the absorber into the energy transfer loop in time δt (seconds) for which the isolation received is δI (Joules).

This is then integrated over the period being considered, say, a day, neglecting negative values of δQ since the system design ensures that energy cannot flow from storage and be lost to the surroundings via the absorbers.

The value of U increases both with δT , and with V .

4. Appendix 4: Model parameters definition

Tilt conversion due to seasonal change

Although the angles of tilt for the SWHs were assumed all to be 25 degrees from the horizontal, there is still a variation in direct normal radiation on the surface of the SWH collector due to seasonal changes. To determine these, data for Cape Town was used from the program SOLATILT, and is presented in full below.

Average solar radiation (W/day)	Tilt angle	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Ave
	0.0°	7956	7177	5887	4207	2946	2390	2684	3462	4707	6291	7552	7952	5268
	5.0°	7963	7285	6094	4464	3198	2630	2933	3694	4894	6416	7583	7931	5424
	10.0°	7923	7351	6266	4696	3432	2855	3166	3906	5054	6505	7572	7865	5549
	15.0°	7838	7373	6401	4900	3646	3064	3381	4097	5186	6558	7517	7755	5643
	20.0°	7717	7352	6499	5076	3840	3256	3576	4264	5290	6574	7421	7620	5707
	25.0°	7565	7288	6557	5222	4010	3428	3751	4406	5364	6553	7302	7447	5741
	30.0°	7370	7182	6577	5337	4157	3579	3903	4523	5408	6494	7142	7233	5742
	35.0°	7133	7046	6557	5420	4278	3709	4031	4614	5421	6399	6944	6978	5711
	40.0°	6856	6870	6499	5470	4374	3816	4135	4677	5404	6269	6707	6686	5647
45.0°	6541	6655	6402	5487	4443	3899	4214	4713	5356	6107	6435	6359	5551	
Solar radiation multipliers relative to horizontal	Tilt angle	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Ave
	0.0°	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
	5.0°	1.00	1.02	1.04	1.06	1.09	1.10	1.09	1.07	1.04	1.02	1.00	1.00	1.04
	10.0°	1.00	1.02	1.06	1.12	1.16	1.19	1.18	1.13	1.07	1.03	1.00	0.99	1.08
	15.0°	0.99	1.03	1.09	1.16	1.24	1.28	1.26	1.18	1.10	1.04	1.00	0.98	1.11
	20.0°	0.97	1.02	1.10	1.21	1.30	1.36	1.33	1.23	1.12	1.04	0.98	0.96	1.14
	25.0°	0.95	1.02	1.11	1.24	1.36	1.43	1.40	1.27	1.14	1.04	0.97	0.94	1.16
	30.0°	0.93	1.00	1.12	1.27	1.41	1.50	1.45	1.31	1.15	1.03	0.95	0.91	1.17
	35.0°	0.90	0.98	1.11	1.29	1.45	1.55	1.50	1.33	1.15	1.02	0.92	0.88	1.17
	40.0°	0.86	0.96	1.10	1.30	1.48	1.60	1.54	1.35	1.15	1.00	0.89	0.84	1.17
45.0°	0.82	0.93	1.09	1.30	1.51	1.63	1.57	1.36	1.14	0.97	0.85	0.80	1.16	

Good recorded data exists for the period 5 August 2003 to 31 January 2004, with some gaps due to logger malfunctions within this period. Thus, the multipliers for August through January were selected from the table, as highlighted, for these months. This data set can also be used then for input to any range of SWH tilt angles.

Azimuth adjustment

The optimal orientation for a SWH is facing due true north. Deviation from this results in a lowering of the overall volume of hot water produced, due to a lower direct normal radiation on the collector. Modelling this deviation has only been performed accurately using a dynamic software approach, for example using the software TRNSYS.

In attempting to approximate the correction in solar radiation due to azimuth deviation, it was fortunate that the close-coupled house that was used as input to the model represented an extreme of the azimuth orientations of the Kuyasa houses. House 56013 had azimuth orientation of 52 degrees. Note however that azimuth corrections due to eastward or westward deviations were not modelled i.e. they were assumed to be the same in either direction.

A further complexity in assessing this parameter is the fluctuation due to change in season. This too was not modelled. Instead, a first approximation of the impact of

azimuth was using the cosine of the azimuth angle, in order to determine a multiplier for the direct normal solar radiation on the collector. This was later refined to be a power of the cosine of the azimuth angle, in order to force a correlation between azimuth factors reported in the literature and the actual azimuth orientations of the four houses. The cosine function was selected since it forms the first-order factor in a dynamic analysis.

Table 6-2 indicates through the use of orange-shaded cells the interpolated azimuth correction factors for the four houses, based on the New Zealand data in Figure 6-5.

Table 6-2: Interpolation of azimuth correction factors (house numbers in brackets)

Azimuth		Tilt angle			
		0	20	25	40
North	0	0.85	0.97	0.98	1
East	30	0.85	0.94	0.94	0.95
	(56586) 34	0.85	0.93	0.93	0.94
	(55747) 44	0.85	0.91	0.91	0.91
	(54610) 49	0.85	0.90	0.90	0.89
	(56013) 52	0.85	0.90	0.89	0.88
	60	0.85	0.88	0.88	0.86

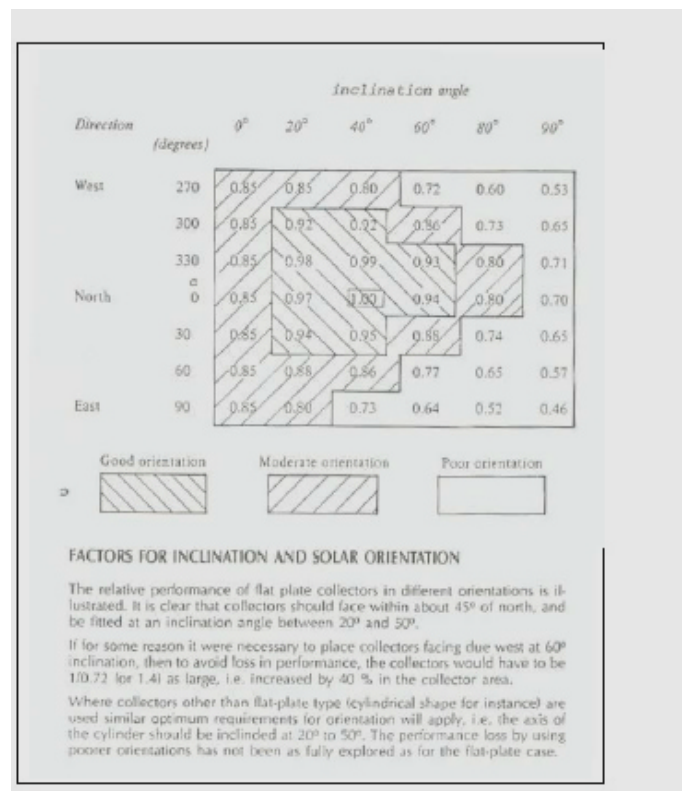


Figure 6-5: Tilt and azimuth correction factors⁹

⁹ Code of Practice for Manufacturing and Installation of Solar Water Heating Systems in New Zealand. Energy Efficiency and Conservation Authority and Solar Industries Association, 12 July 2003 (Version 1). Reproduced from NZS 4614 (New Zealand Standard 4614).

The power factor was set at 0.3 i.e. the azimuth correction factor = $\cos^{0.3}(\text{azimuth angle})$. This resulted in the following azimuth correction factors (Table 6-3):

Table 6-3: Azimuth correction factors

House number	Azimuth	Azimuth correction factor
56586	34° east of north	0.95
55747	44° east of north	0.91
54610	49° east of north	0.88
56013	52° east of north	0.86

These figures correlate well with the interpolated New Zealand data, for a tilt angle of 25 degrees to the horizontal, as set out in Table 6-2.

Overall system efficiency: lower bound

The inputs to the validation model evolving from the draw-down data are as follows:

Input parameters		Units	House 56013
A	Cold water temperature – daily average	Deg C	25.1
B	Collector area	M ²	1.4
C	Horizontal solar radiation on collector	W/m ² /day	7080 ¹⁰
D	Tilt conversion factor from SOLATILT	for 25 deg	1.040
E	Azimuth angle (θ)	degrees	52
F	Azimuth conversion factor	$\cos^2(\theta)$	0.86
G	Hot water temp in tank – daily average	Deg C	43.01
H	Storage tank volume	Litres	100
J	Specific heat capacity of water	kJ/degC/litre	4.187
K	Energy conversion factor	kWh/MJ	3.6
Outputs		Units	House 56013
O1	Lower overall system efficiency	%	36.9

Overall system efficiency: upper bound

A statistical approach was taken in then determining the upper bound for the system efficiencies¹¹. The measured data for the four houses was used to calculate each system's daily performance. For each day, the energy calculated to be in the water (using average hot water demand, and cold and hot water temperatures) was divided by the measured solar radiation. This data set was reduced by excluding those days where the system efficiency was calculated as being below the minimum of 36.9%. These four sets of data were then arranged in descending numerical order, as presented in Table 6-4, and the statistical processing as detailed in Section 4.3.3 applied to them.

¹⁰ Between 08:00 and 19:00

¹¹ It should be noted that a SWH system does not have a constant efficiency, since any change in any of the input parameters will result in a changed overall system efficiency.

Table 6-4: System efficiencies above 36.9%

56013	54610	55747	56586
93.1%	185.4%	109.1%	192.4%
70.1%	164.2%	102.4%	190.9%
63.8%	98.9%	100.5%	164.0%
59.4%	92.7%	99.8%	127.6%
57.6%	88.8%	76.9%	92.5%
53.5%	84.4%	70.3%	81.2%
47.4%	84.4%	59.3%	71.1%
44.5%	84.2%	58.6%	68.8%
43.1%	79.5%	49.2%	68.6%
41.8%	78.9%	48.2%	67.7%
41.3%	75.5%	47.6%	65.4%
40.6%	71.7%	46.5%	60.4%
40.3%	71.4%	45.0%	60.3%
38.6%	68.4%	44.5%	59.1%
38.6%	67.9%	42.3%	57.6%
37.3%	67.5%	40.3%	57.6%
37.1%	63.5%	39.0%	55.8%
36.6%	62.9%	38.6%	55.4%
36.6%	62.3%	38.5%	55.0%
34.6%	61.5%	35.7%	54.1%
34.3%	61.0%	35.4%	53.4%
33.8%	60.8%	34.9%	53.3%
33.7%	60.3%	34.6%	52.1%
33.4%	60.2%	34.5%	51.7%
33.4%	60.1%	34.3%	51.1%
32.1%	58.4%	34.2%	50.0%
32.1%	58.1%	33.8%	48.1%
31.9%	58.0%	33.1%	46.3%
31.9%	57.6%	32.7%	45.1%
31.7%	56.6%	31.3%	44.7%
31.3%	55.3%	30.0%	43.8%
31.3%	55.3%	29.0%	43.1%
30.4%	54.7%	29.0%	42.6%
30.2%	54.2%	28.9%	42.3%
30.1%	53.1%	28.0%	41.4%
29.8%	52.6%	27.8%	41.2%
29.7%	51.2%	26.9%	41.2%
29.5%	51.1%	26.8%	40.0%
29.2%	50.6%	26.6%	39.3%
29.1%	50.6%	26.6%	38.0%
29.1%	49.9%	26.6%	38.0%
29.0%	49.7%	26.5%	37.8%
29.0%	49.6%	26.3%	37.5%
28.9%	49.5%	26.2%	36.6%
28.5%	49.4%	26.2%	35.4%
28.4%	49.2%	26.1%	35.1%
28.3%	49.1%	26.0%	34.8%
28.1%	48.7%	25.8%	34.7%
28.1%	48.6%	25.8%	34.0%
27.9%	48.6%	25.6%	34.0%
26.7%	48.6%	25.5%	33.8%

26.7%	48.0%	25.3%	33.7%
26.1%	47.3%	24.9%	33.3%
26.1%	46.8%	24.6%	33.3%
25.9%	46.7%	24.6%	33.2%
25.9%	46.5%	24.4%	32.9%
25.7%	46.2%	24.0%	32.8%
25.3%	46.0%	23.8%	32.4%
24.8%	45.2%	23.7%	32.0%
24.8%	45.0%	23.7%	32.0%
24.7%	44.9%	23.1%	31.9%
24.6%	44.3%	23.1%	31.7%
24.6%	43.7%	23.0%	31.6%
24.4%	43.6%	22.5%	31.5%
23.8%	42.8%	22.4%	31.4%
23.5%	42.7%	22.4%	31.0%
23.3%	40.8%	22.3%	30.9%
22.9%	40.5%	22.1%	30.3%
22.6%	40.5%	22.1%	30.1%
22.5%	40.4%	21.6%	30.0%
22.4%	40.3%	21.3%	29.2%
22.1%	40.1%	21.2%	29.0%
21.8%	39.8%	21.0%	28.9%
21.5%	39.5%	20.9%	28.7%
21.1%	38.5%	20.9%	28.7%
20.9%	38.1%	20.6%	28.6%
20.8%	38.1%	20.6%	28.5%
20.7%	37.8%	20.5%	28.2%
20.4%	37.7%	20.1%	27.9%
20.2%	37.6%	19.8%	27.7%
20.0%	37.0%	19.3%	27.1%

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