# Field Investigation of 18 Solar-Assisted Domestic Hot Water Systems With Integral Collector Storage

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## ABSTRACT

The purpose of this field investigation was to verify the energy performance of solar-assisted residential domestic hot water (DHW) systems in the community of Civano in Tucson, Arizona. DHW systems in 18 homes were monitored for 15 to 24 months. Each system incorporates an Integral Collector Storage (ICS) panel and a tank-type water heater. System variations include nine systems with electric water heaters and nine systems with gas-fired water heaters, four of which also provide space heating. Energy impacts of pipe lengths and hot water recirculation systems are also examined. Results show that a properly installed and operated system with an electric water heater has an annual solar fraction between 0.48 and 0.66. Systems with extensive piping can consume approximately 200% as much energy per gallon as the best systems, and recirculation systems combined with ICS can result in energy consumption that is approximately 600% higher than a non-solar DHW system[1].

## Introduction

### Civano: A Sustainable Community

Performance goals for homes built at the Community of Civano in Tucson, Arizona include a 50% reduction in heating, cooling, and domestic hot water energy consumption compared to the 1993 Model Energy Code benchmark, the beneficial use of solar technologies, and reduced potable water consumption. Energy efficiency measures used in some of the homes include photovoltaic systems, solar hot water systems, passive solar space heating, exterior window shading, and water conservation systems. When completed in 2010, the community will include 1,600 homes and 1.3 million square feet of commercial space.

### Field Investigation Objectives

The objective of the field investigation was to verify that the homes, including the DHW systems, were meeting the requirements of the Civano Energy Code. Questions to be answered in the DHW portion of the study include:

1. What is the annual amount of non-solar energy consumed per household for DHW?
2. What fraction of the total DHW energy requirement was provided by solar energy?
3. What physical system characteristics affect the efficiency, and to what degree?
4. What impact do various operational schedules and settings have on the system efficiencies?

[1] Based on an energy/volume comparison to SRCC baseline values for Tucson, AZ (5).

## System Descriptions

### Basic System

Of the 18 systems in the study, half have electric water heaters, while the other half have gas water heaters. Four of the nine gas water heaters have an integrated heat exchanger that is used to supply space heating. Each system includes the following components:

1. 40-gallon ICS panel mounted due south at a 35º tilt.
2. Houses (2, 3, 6, 7, 10, & 20) have ICS panels mounted on the roof of a detached garage. They have one-way pipe lengths of 120 feet.
3. 40- or 50-gallon tank-type water heater, gas or electric
4. Manual control valves with two modes: 1.) solar-preheat 2.) solar-only
5. Tempering valve with a temperature range of 110ºF to 170ºF
6. Pressure and temperature relief valve on the tank
7. Pressure-only relief valve on the ICS panel
8. Four houses have a domestic hot water circulation loop serving the fixtures within the house. Each house uses a different method or schedule to control the pump.

The collectors are manufactured by Thermal Conversion Technology, Inc. and constructed with four-inch (102 mm) copper tubing in an insulated aluminum panel. The insulated glazing system consists of a single pane of low-iron glass on the exterior and a thin polymer film as the interior glazing. Some specifications and Solar Rating and Certification Corporation (SRCC) nominal performance statistics are listed in Table 1. Some specifications of the backup water heaters are indicated in Table 2.

**Table 1. ICS Collector/System Specifications - TCT, Inc. Model PT-40**

| Heat Loss | | Area | | Volume | | SEF | |
|---|---|---|---|---|---|---|---|
| Btu/°F | W/°C | ft² | m² | (gal) | (l) | Electric | Gas |
| 17 | 9 | 32.1 | 3.0 | 40 | 151 | 1.6 | 1.0 |

**Table 2. Water Heater Specifications [1]**

| House numbers | Water Heater | | | | | Notes |
|---|---|---|---|---|---|---|
| | Type | EF | RE | UA[1] | | |
| | | | | Btu/h·F° | *j/h·K°* | |
| 1,2,6,19,20 | gas | 0.57 | 0.76 | 9.2 | *17.5* | |
| 3,7,10,12 | electric | 0.91 | 0.98 | 2.5 | *4.8* | |
| 4,8,11,16 | electric | 0.86 | 0.98 | 4.1 | *7.8* | |
| 5,14,15,18 | gas | 0.58 | 0.79 | 9.6 | *18.3* | 2 |
| 9 | electric | 0.90 | 0.98 | 2.8 | *5.4* | |

1. Tank losses only. Does not represent energy lost due to combustion inefficiencies.
2. Water heaters have integral heat exchanger for space heat

### Systems with Integral Space Heating

Four houses (5, 14, 15, & 18) have integral heat exchangers in the water heater that serve space heating systems via a dedicated closed-loop and fan-coil unit. One of these systems, House 14, had to be excluded from the study due to insufficient domestic hot water use data.

## Data Collection

### Field Survey

During the initial site visits each system was carefully inspected and tested. Water heater model numbers where verified and system set points and valve positions were observed and noted. System settings were recorded every three months during site visits so that appropriate adjustments could be made in the analysis of the data.

### Long-Term Monitoring

The DHW system in each home was monitored with a water meter and as many as 7 single-channel data loggers. Table 3 lists the parameters measured and the sampling and storage intervals of the data loggers. Water meters were installed in the cold-water side of the DHW system upstream of the cold-water branch to the mixing valve. A temperature data logger was installed downstream of the mixing valve to measure the temperature of the corresponding flow.

**Table 3. Data Measurement Intervals**

| Parameter | Sampling Interval |
|---|---|
| Hot water use | Each gallon |
| Hot water temperature | Every 20 seconds; maximum value recorded every 30 minutes |
| Mains water temperature | Every 20 seconds; minimum value recorded every 30 minutes |
| Tank temperature | Every 40 seconds; hourly average value recorded |
| Tank room air temperature | Every hour |
| Electric water heater current | Every 40 seconds; hourly average value recorded |
| Gas water heater run-time | Every 1.2 seconds; hourly average value recorded |
| Space heating pump run-time | Every 1.2 seconds; hourly average value recorded |

## Analysis

### Overview

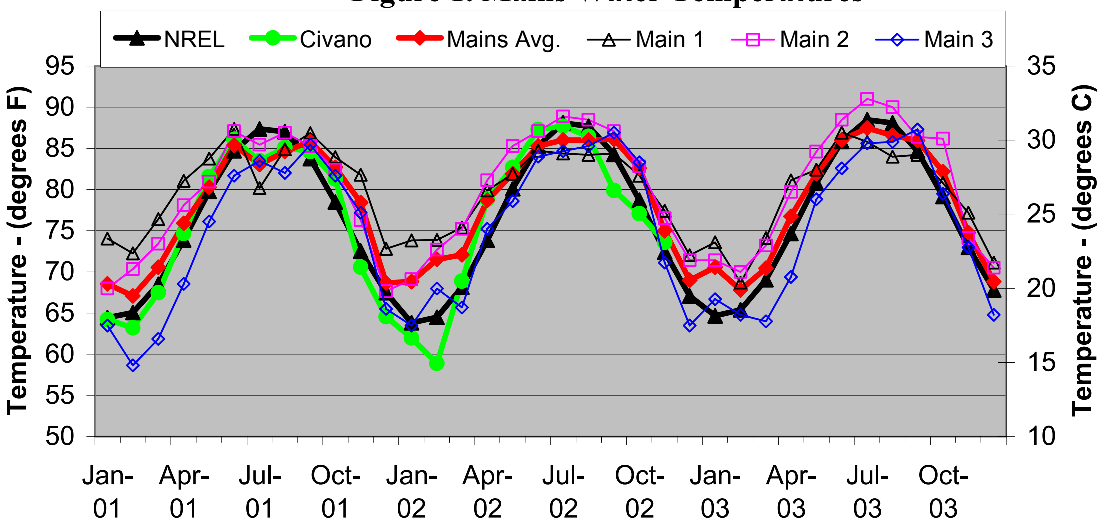
The analysis of the data is configured as an energy balance of the water in the backup water heater. Energy flowing into the tank consists of the water heater input and hot water from the solar collector. Energy flowing out of the tank consists of hot water delivered to the fixtures, heat losses of the tank, and additional system heat losses. Equation (1) summarizes the energy balance of the tank.

$$Q_{wh} + Q_{solar} = Q_{del} + Q_{tank} + Q_{space} + Q_{pipe} \qquad (1)$$

## Mains Water Temperature

Mains water temperatures were recorded on site, but in an effort to limit monitoring costs and redundancy, data were only collected in three of the homes. The average of the three hourly volume-weighted site measurements is labeled as "Civano" in Figure 1. After the first year, data loggers were relocated to homes with higher water use, but data logger and meter failures resulted in a lack of data. As a substitute for lost data, the mains water temperatures were calculated using annual and average monthly outdoor air temperatures recorded on site. The equation (2) used was developed by researchers at NREL to establish a universal mains water temperature calculation method for comparing the performance of DHW systems in any climate [2]. Figure 1 also provides a comparison between the calculated temperatures and monthly sample temperatures recorded by Tucson Water at three different mains serving the neighborhood. A "Mains Average" is shown for comparison. The correlation between calculated and measured values appears to be good and is believed to have little or no effect on the conclusions of the study.

**Figure 1. Mains Water Temperatures**




$$T_{mains} = (T_{amb,avg} + offset) + ratio(\Delta T_{amb,\max}/2) \sin(0.986(day\# - 15 - lag) - 90) \quad (2)$$

where

| | | |
|---|---|---|
| 0.986 | = degrees/day (360/365) | (2a) |
| *day#* | = 30 * month# - 15 | (2b) |
| *offset* | = 6°F (3.3°C) | |
| *ratio* | $= 0.4 + 0.01(T_{amb,avg} - 44°F(24.4°C))$ | (2c) |
| *lag* | $= 25 + 1.0(T_{amb,avg} - 44°F(24.4°C))$ | (2d) |

**Volume-Weighted Hot Water Temperature**

Each gallon (3.8 l), $v$, of hot water recorded is aligned with the maximum hot water temperature recorded during the coincident half hour. Hot water temperatures recorded during time periods when no hot water was drawn are excluded from the average. A volume-weighted hot water temperature is calculated using Equation (3).

$$T_{vw,hot} = \sum_{n=1}^{n} \left( v_n T_{n,hot} \right) \Big/ \sum_{n=1}^{n} \left( v_n \right) \qquad (3)$$

**Energy Content of Hot Water Delivered to Fixtures**

The net energy to heat the water is calculated by multiplying the mass of water used during a specific time period by the difference between the average mains and the volume-weighted hot water temperatures for each home. The minimum time period used when evaluating these calculations is one month. The energy content of the water delivered to plumbing fixtures is computed as

$$Q_{del} = v c_p \rho \left( T_{\text{vw,hot}} - T_{mains} \right) \qquad (4)$$

Because each system has different set points and operating characteristics, average monthly water temperature rises for all the houses were calculated so that individual system performance characteristics could be compared. Table 4 lists the values used to normalize water volumes for temperature.

**Table 4. Average Water Temperature Rise for All Systems**

| Temp. | Jan | Feb | Mar | Apr | May | Jun | Jul | Aug | Sep | Oct | Nov | Dec | Annual |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| °F | 55.5 | 55.3 | 52.3 | 46.3 | 39.2 | 35.4 | 30.6 | 31.5 | 34.0 | 37.8 | 41.7 | 49.5 | 43.4 |
| °C | 30.8 | 30.7 | 29.1 | 25.7 | 21.8 | 19.7 | 17.0 | 17.5 | 18.9 | 21.0 | 23.2 | 27.5 | 24.1 |

Normalized hot water volumes are calculated for each house as

$$V_{norm} = V_{meas} \left( \Delta T_{meas} / \Delta T_{avg} \right) \qquad (5)$$

**Water Heater Heat Losses**

The overall heat loss coefficient of a gas-fired water heater includes the heat lost to the surrounding air as well as the inefficiencies of combustion. Equation (6) [3] expresses the total heat loss coefficient as

$$UA_{t,gas} = \frac{\left( 1/EF - 1/RE \right)}{\left( T_{\tan k,DOE} - T_{amb,DOE} \right) \left( \dfrac{24\ \text{h/day}}{q_{out}} - \dfrac{1}{RE \cdot p_{on}} \right)} \qquad (6)$$

Heat loss to the ambient air for a gas-fired water heater, $UA_{amb,gas}$, is proportionate to the Recovery Efficiency and is expressed as

$$UA_{amb,gas} = UA_{t,gas}RE \quad (7)\ [4]$$

Once $UA_{\text{t,gas}}$ is determined, the burner efficiency of a gas water heater can be calculated as

$$\eta_{burner} = RE + UA_{t,gas}(T_{\tan k} - T_{amb})/(p_{on}) \quad (8)\ [4]$$

For electric water heaters, the energy conversion efficiency of the elements is 1.0 and the total heat loss and ambient heat loss are one in the same. The heat loss is expressed as

$$UA_{amb,elec} = q_{out}(1/EF - 1)/(24(T_{\tan k} - T_{amb})) \quad (9)\ [2]$$

The tank energy loss over a period of time for both types of water heaters is then defined as

$$Q_{\tan k} = \sum_{t=1}^{t}(T_{t,\tan k} - T_{t,amb})UA_{amb} \quad (10)$$

### Water Heater Contribution

The total energy input for an electric water heater into the system over a period of time (t) is computed as

$$Q_{wh} = \sum_{t=1}^{t} I_t(V) \quad (11a)$$

The total energy input for gas-fired water heater into the system over a period of time (t) is computed as

$$Q_{wh} = \eta_{burner}\left[p_{\text{on}}\sum_{t=1}^{t}RT_{wh} + p_p\left(t - \sum_{t=1}^{t}RT_{wh}\right)\right] \quad (11b)$$

The pilot light input requirement is assumed to be 400 Btu/h (422 j/h). Equation (11b) is derived on the assumption that the listed main burner capacity includes the pilot light.

### Additional System Heat Losses

Piping heat loss is the calculated system heat loss minus the calculated water heater standby losses. The resulting piping heat loss coefficient is then multiplied by the temperature difference between the mixed water and the tank room temperature for each time interval. The calculated system heat loss for each house is determined by summing the energy used by the water heater during a period when no water is used (typically a week-long vacation). The average hourly energy used during the vacation period is then divided by the difference between the average tank temperature and the average tank room temperature for the same time period.

$$UA_{pipe} = \left[\sum_{t=1}^{t}RT_{wh}P_{on} \Big/ ((t)(T_{\tan k,avg} - T_{amb,avg}))\right] - UA_{amb} \quad (12)$$

The additional pipe heat loss is then defined as

$$Q_{pipe} = \sum_{t=1}^{t} \left(T_{t,pipe} - T_{t,amb}\right) UA_{pipe} \qquad (13)$$

Additional pipe heat loss coefficients were generally found to be less than tank heat loss coefficients expect in systems that had thermosiphon conditions.

### Space Heating Energy

The output capacity of the space heating system was calibrated using Equation (14) for selected time periods in which no domestic water was drawn.

$$q_{coil} = \left(Q_{wh} - Q_{\tan k} - Q_{pipe}\right) \sum_{t=1}^{t} RT_p \Big/ \sum_{t=1}^{t} RT_{wh} \qquad (14)$$

The energy demand of the space heating system over time can then be found by multiplying the runtime of the hydronic pump by the output rate of the coil as shown by

$$Q_{space} = q_{coil} \sum_{t=1}^{t} RT_p \qquad (15)$$

### Solar Contribution and Fraction

Once all the other energy losses and gains of the tank are calculated, the solar energy contribution can be determined as shown in Equation (16). Rearranging Equation (1) yields

$$Q_{solar} = -\left(Q_{del} + Q_{\text{tank}} + Q_{pipe}\right) - Q_{wh} \qquad (16)$$

The solar fraction is then defined as

$$F_{solar} = -\left(\frac{Q_{solar}}{Q_{pipe} + Q_{del} + Q_{\text{tank}}}\right) \qquad (17)$$

## Results

### Group A – Systems with Short Pipe Lengths and Electric Water Heaters

Group A (Table 5) had the best performing systems of the study with a normalized energy use of 209 Btu/gal (58 j/l) for the group as a whole. The three houses that used the solar-only mode of operation during the summer had the highest solar fraction. House 11 had the highest solar fraction and the lowest normalized energy use due to a moderate daily hot water demand. The normalized energy use of House 16 was the highest (worst) despite a high solar fraction due to the disproportionately large standby losses associated with low daily hot water demand.

Normalized values account for variations in volume as well as temperature rise. The average monthly temperature rise for all 17 systems are was used as the basis for normalization. Values are listed in Table 4.

Hot water use ratios are given as an indication of hot water use diversity throughout the year. Average monthly hot water use was calculated using only the days in which each house was occupied. The largest variations between households are believed to be due to guests since only the number of permanent occupants was known.

The solar collector of House 12 was homemade and consisted of a single 40-gallon cylindrical tank in an insulated box with single glazing. Data for House 12 were excluded from the group average values for normalized energy to provide an additional performance comparison.

**Table 5. Electric WH, Short Pipes (Group A) - Annual Summary**

| House | WH Energy Use kWh/yr | Occupancy | | Hot Water Use | | | | Hot Water Temperature Rise | | Normalized Site Energy Use | | $F_{solar}$ |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | No. | Days | Annual Average | | Ratios of Monthly Averages | | | | | | |
| | | | | Gal/d | *l/d* | Max/Avg | Min/Max | °F | *°C* | Btu/gal | *j/l* | |
| 4 | 1,512 | 3 | 365 | 76 | *288* | 1.22 | 0.65 | 40.1 | *22.3* | 201 | *56* | 0.52 |
| 8 | 1,442 | 3 | 363 | 72 | *272* | 1.24 | 0.65 | 36.1 | *20.1* | 227 | *63* | 0.48 |
| 9[1] | 450 | 2 | 351 | 17 | *66* | 1.75 | 0.32 | 39.6 | *22.0* | 274 | *76* | 0.57 |
| 11[1] | 443 | 2 | 355 | 25 | *96* | 1.16 | 0.73 | 45.4 | *25.2* | 161 | *45* | 0.66 |
| 12 | 1,003 | 2 | 343 | 29 | *108* | 1.62 | 0.35 | 49.9 | *27.7* | 304 | *85* | 0.32 |
| 16[1] | 334 | 1 | 346 | 11 | *43* | 1.35 | 0.52 | 34.3 | *19.1* | 365 | *102* | 0.62 |
| **Avg.** | **836[2]** | **2.2** | **354** | **41** | ***155*** | **1.20** | **0.62** | **40.6[3]** | ***22.5[3]*** | **209[2]** | ***58[2]*** | **0.54[2]** |

1. System in "solar only" mode during summer.
2. Data from House 12 are excluded from this value due to differences in collector construction.
3. Data from House 16 are excluded from this value due to improper system operation by the occupant.

## Group B – Systems with Long Pipe Lengths and Electric Water Heaters

The results from these two homes (Table 6) indicate that long pipe lengths between the collector and the tank have a significant impact on the system performance. Compared to the average performance of the systems in Group A, these systems use approximately 200% more energy per volume of water on an annual basis. The higher solar fraction of House 3 may be due to fact that they occupant's used 39% of their daily hot water in the afternoon hours compared to 29% for the occupants of House 7. It should also be noted that House 7 includes an "on demand" hot water recirculation system, which appears to have little impact on the performance of this system.

**Table 6. Electric WH, Long Pipes (Group B) – Annual Summary**

| House | WH Energy Use kWh/yr | Occupancy | | Hot Water Use | | | | Hot Water Temperature Rise | | Normalized Site Energy Use | | $F_{solar}$ |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | No. | Days | Annual Average | | Ratios of Monthly Averages | | | | | | |
| | | | | Gal/d | *l/d* | Max/Avg | Min/Max | °F | *°C* | Btu/gal | *j/l* | |
| 3 | 1,452 | 2 | 362 | 31 | *117* | 1.37 | 0.59 | 42.3 | *23.5* | 455 | *127* | 0.43 |
| 7 | 1,447 | 2 | 356 | 33 | *123* | 1.24 | 0.70 | 48.2 | *26.8* | 384 | *107* | 0.36 |
| **Avg.** | **1,450** | **2** | **359** | **32** | ***120*** | **1.30** | **0.69** | **45.3** | ***25.2*** | **416** | ***116*** | **0.40** |

## Group C – Systems with Long Pipe Lengths and Hot Water Recirculation Systems

The results of the systems in this group were clearly divided between well-controlled and poorly-controlled hot water recirculation systems. The results from the systems in Group C1

(Table 7) demonstrate how a combination of long pipe runs and a poorly-controlled hot water recirculation system can significantly increase system energy requirements. The energy use per gallon (liter) for House 10 was found to be almost 1,400% higher than the homes in Group A. The recirculation in House 6 ran a minimum of 15 min/h from 5 a.m. to 7 p.m. and 100% for some of the months. The pump in House 10 ran 20 min/h in the morning and evening for a total of 5 hours and 40 minutes per day.

**Table 7. Long Pipes, HWR, Poor Control (Group C1) - Annual Summary**

| House | WH Energy Use Therms (kWh/yr) | Occupancy | | Hot Water Use | | | | Hot Water Temperature Rise | | Normalized Site Energy Use | | $F_{solar}$ |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | No. | Days | Annual Average | | Ratios of Monthly Averages | | | | | | |
| | | | | Gal/d | *l/d* | Max/Avg | Min/Max | °F | *°C* | Btu/gal | *j/l* | |
| 6[1] | 202 (5,929) | 2 | 285 | 25 | *94* | 1.59 | 0.28 | 46.4 | *25.8* | 2,667 | *743* | N/A |
| 10 | (6,530) | 2 | 344 | 21 | *81* | 1.88 | 0.32 | 45.3 | *25.2* | 2,911 | *811* | N/A |
| **Avg.** | **N/A** | **2** | **315** | **23** | ***87*** | **1.52** | **0.35** | **45.8** | ***25.5*** | **N/A** | ***N/A*** | **N/A** |
| **1.** Gas water heater was turned off during summer months, but system was left in "solar preheat" mode. | | | | | | | | | | | | |

The results from the systems in Group C2 (Table 8) demonstrate how better pump controls can limit energy losses in an ICS solar DHW system. The manually operated HWR system in House 19 appears to be less of a factor than the large hot water demand of the occupants.

**Table 8. Long Pipes, HWR, Better Control (Group C2) – Annual Summary**

| House | WH Energy Use Therms (kWh/yr) | Occupancy | | Hot Water Use | | | | Hot Water Temperature Rise | | Normalized Site Energy Use | | $F_{solar}$ |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | No. | Days | Annual Average | | Ratios of Monthly Averages | | | | | | |
| | | | | Gal/d | *l/d* | Max/Avg | Min/Max | °F | *°C* | Btu/gal | *j/l* | |
| 7 | (1,447) | 2 | 356 | 33 | *123* | 1.24 | 0.70 | 48.2 | *26.8* | 384 | *107* | 0.36 |
| 19[1] | 110 (3,232) | 5 | 334 | 56 | *214* | 1.17 | 0.73 | 41.1 | *20.6* | 618 | *172* | 0.34 |
| **Avg.** | **N/A** | **3.5** | **345** | **44** | ***167*** | **1.14** | **0.76** | **43.9** | ***24.4*** | **N/A** | ***N/A*** | **N/A** |
| **1.** Gas water heater | | | | | | | | | | | | |

## Group D – Systems with Long Pipe Lengths and Gas-Fired Water Heaters

The results from the systems in Group D vary widely due to the range in hot water demand and the presence of a thermosiphon between the water heater and collector in House 1. A check valve was installed later in the study that reduced energy consumption per unit volume by approximately 50%. Houses 2 and 20 have identical systems. The differences here appear to be due to the extremely low water use of the occupant in House 20 and the fact that they operate the water heater all summer long. Summer gas consumption in House 20 is primarily pilot light energy for four months.

**Table 9. Gas-Fired WH, Long Pipes (Group D) - Annual Summary**

| House | WH Energy Use Therms (kWh/yr) | Occupancy | | Hot Water Use | | | | Hot Water Temperature Rise | | Normalized Site Energy Use | | $F_{solar}$ |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | No. | Days | Annual Average | | Ratios of Monthly Averages | | | | | | |
| | | | | Gal/d | *l/d* | Max/Avg | Min/Max | °F | *°C* | Btu/gal | *j/l* | |
| 1[1] | 134 (3,925) | 2 | 358 | 28 | *106* | 1.64 | 0.34 | 37.1 | *20.6* | 1,571 | *438* | 0.22 |
| 2[2] | 60 (1,769) | 1 | 357 | 27 | *101* | 1.56 | 0.47 | 44.3 | *24.6* | 621 | *173* | 0.39 |
| 20[1] | 60 (1,768) | 1 | 319 | 16 | *61* | 1.33 | 0.48 | 41.3 | *23.0* | 1,242 | *346* | 0.30 |
| **Avg.** | **84.9 (2,487)** | **1.3** | **345** | **24** | ***90*** | **1.42** | **0.50** | **40.7** | ***22.6*** | **1,145** | ***319*** | **0.29** |

**1.** Gas water heater
**2.** Gas water heater was turned off during summer months, but system was left in "solar preheat" mode.

## Group E – Systems with Integral Space Heating and Gas-Fired Water Heaters

The results from the systems in Group E (Table 10) vary widely due to various thermosiphons in two of the systems. The thermosiphon in House 15 occurred within the piping to and from the solar collector and consequently the heat losses are calculated as delivered hot water due to the fact that the hot water meter is within the loop. The thermosiphon in House 18 occurred within the space heating piping loop and accounted for more energy use on an annual basis than the intentional space heating. The system in House 5 performed as intended and achieved the lowest (best) annual normalized energy use of the eight houses in the study with gas-fired backup water heaters. Annual space heating loads in these homes were only 55% to 75% higher than the annual DHW loads.

**Table 10. Gas-Fired WH, Integral Space Heating (Group E) - Annual Summary**

| House | WH Energy Use Therms (kWh/yr) (note 4) | Occupancy | | Hot Water Use | | | | Hot Water Temperature Rise | | Normalized Site Energy Use (note 4) | | $F_{solar}$ (note 3) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | No. | Days | Annual Average | | Ratios of Monthly Averages | | | | | | |
| | | | | Gal/d | *l/d* | Max/Avg | Min/Max | °F | *°C* | Btu/gal | *j/l* | |
| 5 | 64 (1,889) | 3 | 362 | 25 | *96* | 1.24 | 0.51 | 52.3 | *29.1* | 584 | *163* | 0.13 |
| 15[1] | 51 (1,485) | 3 | 343 | 19 | *72* | 1.85 | 0.24 | 46.7 | *26.0* | 718 | *200* | 0.12 |
| 18[2] | 62 (1,811) | 1 | 348 | 11 | *43* | 1.58 | 0.41 | 47.9 | *26.6* | 1,423 | *397* | 0.11 |
| **Avg.** | **59 (1,728)** | **2.3** | **351** | **19** | ***71*** | **1.51** | **0.60** | **49.6** | ***27.5*** | **889** | ***248*** | **0.12** |

**1.** Thermosiphon in collector pipe loop.
**2.** Thermosiphon in space heating hydronic loop.
**3.** Fraction of DHW, system losses, **and space heating** loads that were attributed to solar.
**4.** Total WH energy use was proportioned by dividing the DHW load by (DHW load + space heating load).

## Source Energy Comparison of System Performance

Source energy multipliers [2] of 3.16 and 1.02 were applied to site energy use of electric and gas-fired water heaters respectively (Table 11). The results are mixed and inconclusive in regards to recommendations of a backup water heater fuel source for ICS solar systems since there were no systems in the study with gas-fired backup water heaters without long pipe runs. A comparison of the normalized source energy use between groups B and D indicates that systems with electric water heaters use approximately 17% more source energy than similar systems with gas-fired water heaters, but the samples are too small to be conclusive.

**Table 11. Source Energy - Annual Summary**

| House or Group | Water Heater Source Energy Use | | Normalized Source Energy Use | |
|---|---|---|---|---|
| | Therms | *kWh* | Btu/gal | *j/l* |
| A | 90.2 | *2,643* | 662 | *184* |
| 12 (A) | 108.2 | *3,170* | 961 | *268* |
| B | 156.3 | *4,581* | 1,316 | *367* |
| 6[1] (C1) | 206.3 | *6,047* | 2,720 | *758* |
| 10 (C1) | 704.0 | *20,634* | 9,200 | *2,564* |
| 19[1] (C2) | 112.5 | *3,296* | 630 | *176* |
| D | 86.6 | *2,537* | 1,127 | *314* |
| E | 60.1 | *1,763* | 907 | *253* |
| 1. Gas water heater | | | | |

**Comparison to SRCC Estimates**

Table 12 lists SRCC simulated system performance values that are used as a basis for comparison. Although the SRCC simulation assumption for collector tilt (23°) is biased towards summer optimization the performance estimates for systems with both types of backup water heaters exceeded all but one of the measured systems in Civano. There are several factors, both, in the simulation assumptions and the installation and operation of the systems at Civano that could have contributed to this. Compared to the measured data, the SRCC assumption for hot water usage overestimates summer usage by approximately 20% and underestimates winter usage by the same amount. Simulation assumptions such as the resolution of the hot water usage schedule and the time step of the simulation can also result in lower system losses if they are not small enough to capture the transient nature of heat loss between water use events. Additional system heat losses and smaller hot water demands for many of the Civano systems also contributed to less than optimal performance. The energy intensity values in Table 12 have been normalized using the average temperature rise of the Civano systems for comparison purposes. The average temperature rise for the SRCC simulation is estimated to be approximately 5°F (2.8°C) greater than the average system at Civano.

**Table 12. SRCC Annual Site Energy Estimates – TCT, Inc. Model PT-40, Tucson, Arizona**

| | Conventional DHW System | | | | ICS DHW System (TCT, Inc. Model PT-40) | | | | |
|---|---|---|---|---|---|---|---|---|---|
| Fuel | Therms/yr | kWh/yr | Btu/gal | j/l | Therms/yr | kWh/yr | Btu/gal | j/l | $F_{solar}$ |
| Electric | 123 | 3,600 | 467 | 123 | 48 | 1,400 | 183 | 48 | 0.61 |
| Gas | 185 | 5,422 | 702 | 186 | 85 | 2,491 | 323 | 85 | 0.54 |

## Conclusions

Solar ICS systems installed on homes with electric water heaters and short plumbing runs operated at an average solar fraction of 0.54, helping to achieve the goals of the Civano Energy Code. However, the performance of other systems was disappointing. It was determined that long pipe lengths between the solar collector and water heater can approximately double the non-solar energy use per unit volume of water when compared to similar systems with shorter pipes. A poorly controlled hot water recirculation system was observed to almost 1,400% more non-solar energy per gallon (liter) of water than a properly installed and operated ICS solar DHW system and approximately 600% more than a conventional DHW system (5). On the other hand, an "on demand" hot water recirculation system had no noticeable impact on energy use. Performance of the ICS systems installed with natural gas auxiliary water heaters was significantly less than with electric water heaters. Solar fraction averaged 31% in four successfully installed and operated systems.

## Nomenclature

| | |
|---|---|
| $\eta_{burner}$ | WH burner efficiency |
| $c_p$ | Specific heat of water |
| EF | DOE Energy Factor |
| $F_{solar}$ | Solar fraction |
| HW | Hot water |
| HWR | Hot water recirculation |
| $I_t$ | Average measured electrical current for time (t) |
| RE | DOE Recovery efficiency |
| $p_{\mathrm{on}}$ | WH main burner energy input rate |
| $p_{\mathrm{p}}$ | Energy input rate of WH pilot light |
| $\rho$ | Density of water |
| $q_{\mathrm{out}}$ | 41,094 Btu/day (12,044 Wh/day) |
| $Q_{wh}$ | Energy gain due to WH operation |
| $Q_{solar}$ | Energy gain due to solar collector |
| $Q_{del}$ | Energy delivered to DHW fixtures |
| $Q_{tank}$ | Energy loss of WH to surroundings |
| $Q_{space}$ | Energy delivered to space conditioning system |
| $Q_{pipe}$ | Energy loss of piping and and/or collector |
| $RT_{\mathrm{wh}}$ | Fractional runtime of WH main burner |
| $T_{\mathrm{n,hot}}$ | HW temperature coincident with volume |
| $T_{\mathrm{vw,hot}}$ | Volume-weighted HW temperature |
| $T_{\mathrm{tank,DOE}}$ | Tank temperature at DOE test conditions 135°F (57.2°C) |
| $T_{\mathrm{amb,DOE}}$ | Ambient air temperature surrounding tank at DOE test conditions 67.5°F (19.7°C) |
| $T_{mains}$ | Mains temperature to DHW system |
| $T_{amb,avg}$ | Annual average ambient air temperature |
| $\Delta T_{amb,\mathrm{max}}$ | Maximum difference between monthly average ambient temperatures |
| $UA_{amb}$ | WH heat loss coefficient to ambient air |
| $UA_{\mathrm{t}}$ | WH total heat loss coefficient |
| $V$ | AC voltage (estimated @ 240 volts) |
| $v$ | Water volume |
| WH | Water heater |

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