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, AZ. 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 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 190% as much energy per gallon as the best systems, and recirculation systems combined with ICS can result in energy consumption that is almost 550% higher than a non-solar DHW system [1].

1. INTRODUCTION

1.1. 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.

1.2. 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 also include:

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

2. SYSTEM DESCRIPTIONS

2.1. 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:

- 40-gallon ICS panel mounted due south at a 35º tilt.

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

- 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.
- 40- or 50-gallon tank-type water heater, gas or electric
- Manual control valves with two modes: 1.) solar-preheat 2.) solar-only
- Tempering valve with a temperature range of 110ºF to 170ºF
- Pressure and temperature relief valve on the tank
- Pressure-only relief valve on the ICS panel
- 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 constructed with four-inch (102 mm) copper tubing in an insulated aluminum panel. The 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 of the backup water heaters are indicated in Table 1.

TABLE 1 - WATER HEATER SPECIFICATIONS [1]

House numbers	Water Heater				Notes
	Type	EF	RE	UA (1)	
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. Btu/h·F° (j/h·K°)
2. Water heaters have integral heat exchanger for space heat

2.2. 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.

3. DATA COLLECTION

3.1. 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 noted every three months during site visits so that appropriate adjustments could be made in the analysis of the data.

3.2. 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 2 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. The water meter for the homes with integral space heating (Houses 5, 14, 15, & 18) had to be placed on the cold-water inlet to the solar collector and the hot water temperature logger was placed on the hot water pipe upstream of the mixing valve due to space constraints. Thus, the energy use per unit volume of these systems has a low bias. Total system energy use is unaffected.

TABLE 2 - 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 s; 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

4. ANALYSIS

4.1. 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.

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

4.2. Mains Water Temperature

Mains (municipal city supply) water temperatures were calculated using annual and average monthly outdoor air temperatures recorded on site. The equation used was developed [2] by researchers at NREL to establish a consistent benchmark for comparing the performance of DHW systems in any climate.

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

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)

Cold water temperatures were also recorded on site, but only in three of the homes in an effort to limit monitoring costs and redundancy. Measurements compared well with the calculated water temperatures for the winter months, but not for the warmer months. This was due to the indoor location of some sensors and the fact that the data loggers were recording the minimum water temperature for each half-hour interval. While this strategy would be acceptable for many locations in the U.S., it does not work in locations where the inlet water temperatures can exceed the indoor air temperatures, as was the case at Civano. The measured data did reveal a small daily increase in water temperature (1.5°F) (0.83°C) from morning to evening, which was applied to the calculation of the delivered DHW energy.

4.3. 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).

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

4.4. 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. 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

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

4.5. 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 (4) [3] expresses the total heat loss coefficient as

$$UA_{t,gas} = \frac{\left(1/EF - 1/RE\right)}{\left(T_{tank,DOE} - T_{amb,DOE}\right)\left(\frac{24\text{ h/day}}{q_{out}} - \frac{1}{RE \cdot p_{on}}\right)} \quad (5)$$

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

$$UA_{amb,gas} = UA_{t,gas} RE \quad [4]\ (6)$$

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

$$\eta_{burner} = RE + UA_{t,gas}\left(T_{tank} - T_{amb}\right)/\left(p_{on}\right) \quad [4]\ (7)$$

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

$$UA_{amb,elec} = q_{out}\left(1/EF - 1\right)/\left(24\left(T_{tank} - T_{amb}\right)\right) \quad [2]\ (8)$$

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

$$Q_{tank} = \sum_{t=1}^{t}\left(T_{t,tank} - T_{t,amb}\right)UA_{amb} \quad (9)$$

4.6. Water Heater Contribution

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

$$Q_{wh} = \sum_{t=1}^{t} I_t(V) \quad (10a)$$

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

$$Q_{wh} = \eta_{burner}\left[p_{\text{on}}\sum_{t=1}^{t} RT_{wh} + p_p\left(t - \sum_{t=1}^{t} RT_{wh}\right)\right] \quad (10b)$$

400 Btu/h (422 j/h) is assumed for the pilot light input requirement. Equation (9b) is derived on the assumption that the listed main burner capacity includes the pilot light.

4.7. 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.

$$UA_{pipe} = \left[\sum_{t=1}^{t} RT_{wh}P_{on} \Big/ \left((t)\left(T_{\text{tan}k,avg} - T_{amb,avg}\right)\right)\right] - UA_{amb} \quad (11)$$

The additional pipe heat loss is then defined as

$$Q_{pipe} = \sum_{t=1}^{t}\left(T_{t,pipe} - T_{t,amb}\right)UA_{pipe} \quad (12)$$

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

4.8. Space Heating Energy

The output capacity of the space heating system was calibrated using Equation (13) for selected time periods in which no domestic water was drawn.

$$q_{coil} = \left(Q_{wh} - Q_{\text{tan}k} - Q_{pipe}\right)\sum_{t=1}^{t} RT_p \Big/ \sum_{t=1}^{t} RT_{wh} \quad (13)$$

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

$$Q_{space} = q_{coil}\sum_{t=1}^{t} RT_p \quad (14)$$

4.9. 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 (14). Rearranging Equation (1) yields

$$Q_{solar} = -\left(Q_{del} + Q_{\text{tank}} + Q_{pipe}\right) - Q_{wh} \quad (15)$$

The solar fraction is then defined as

$$F_{solar} = -\left(\frac{Q_{solar}}{Q_{pipe} + Q_{del} + Q_{\text{tank}}}\right) \quad (16)$$

5. RESULTS

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

Group A (Table 3) had the best performing systems of the study. The data from House 12 were excluded from the calculation of the average values for this group because it is the only system in the study that incorporated a homemade solar collector. Normalized values are account for variations in volume as well as temperature rise. The average annual temperature rise for all the systems is 43.4°F (24.1°C).

TABLE 3 – GROUP A - ANNUAL SUMMARY

House	WH Energy Use kWh/yr	Hot Water Use		Normalized Energy Use		F_{solar}
		Gal/d	*l/d*	Btu/gal	*j/l*	
4	1,512	76	*288*	201	*56*	0.52
8	1,442	72	*271*	227	*63*	0.48
9[1]	450	17	*64*	274	*76*	0.57
11[1]	443	25	*93*	161	*45*	0.66
12	1,003	27	*102*	304	*85*	0.32
16[1]	334	11	*41*	365	*102*	0.62
Avg.	**836**	**40**	***151***	**218**	***61***	**0.54**

1. System in "solar only" mode during summer.

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

The results from these two homes (Houses 3 & 7) 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 190% 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 4 - GROUP B - ANNUAL SUMMARY

House	WH Energy Use kWh	Average Daily Hot Water Use		Normalized Energy Use		F_{solar}
		Gal/d	*l/d*	Btu/gal	*j/l*	
3	1,452	31	*116*	455	*127*	0.43
7	1,447	32	*120*	384	*107*	0.36
Avg.	**1,450**	**31**	***118***	**416**	***116***	**0.40**

5.3. 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 5) 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 more than 1,350% higher than the homes in Group A. The recirculation in House 6 ran a minimum of 15 min/h from 5am to 7pm 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 5 - GROUP C1 - ANNUAL SUMMARY

House or Group	WH Energy Use Therms (kWh)	Average Daily Hot Water Use		Normalized Energy Use		F_{solar}
		Gal/d	*l/d*	Btu/gal	*j/l*	
6[1]	202 (5,929)	19	*74*	2,667	*743*	N/A
10	(6,530)	20	*76*	2,911	*811*	N/A
Avg.	**N/A**	**20**	***75***	**N/A**	***N/A***	**N/A**
1. Gas water heater was turned off during summer months, but system was left in "solar preheat" mode.						

TABLE 6 - GROUP C2 – ANNUAL SUMMARY

House or Group	WH Energy Use Therms (kWh)	Average Daily Hot Water Use		Normalized Energy Use		F_{solar}
		Gal/d	*l/d*	Btu/gal	*j/l*	
7	(1,447)	32	*120*	384	*107*	0.36
19[1]	86 (2,529)	52	*195*	618	*172*	0.34
Avg.	**N/A**	**37**	***138***	**N/A**	***N/A***	**N/A**
1. Gas water heater						

The results from the systems in Group C2 (Table 6) demonstrate how better pump controls can limit energy losses in an ICS solar DHW system. The system in House 19, although manually operated, appears to be less of a factor than the large hot water demand of the occupants.

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

The results from the systems in Group D (Table 7) 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 & 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 7 - GROUP D - ANNUAL SUMMARY

House or Group	WH Energy Use Therms (kWh)	Average Daily Hot Water Use		Normalized Energy Use		F_{solar}
		Gal/d	*l/d*	Btu/gal	*j/l*	
1[1]	134 (3,925)	27	*104*	1,571	*484*	0.22
2[2]	61 (1,777)	26	*99*	621	*173*	0.39
20[1]	60 (1,768)	14	*53*	1,242	*346*	0.30
Avg.	**84.9 (2,487)**	**22**	***85***	**973**	***271***	**0.29**
1. Gas water heater 2. Gas water heater was turned off during summer months, but system was left in "solar preheat" mode.						

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

The results from the systems in Group E (Table 8) vary widely due to various thermosiphons in two of the systems. The losses caused by the thermosiphon in House 15 are disguised as delivered hot water due to the fact that the hot water meter is within the loop. The losses in House 18 occur between heating cycles and end up as space heat within the house.

TABLE 8 - GROUP E - ANNUAL SUMMARY

House or Group	WH Energy Use Therms (kWh)	Average Daily Hot Water Use		Normalized Energy Use		F_{solar}
		Gal/d	*l/d*	Btu/gal	*j/l*	
5	64 (1,889)	25	*95*	584	*163*	0.13
15[1]	51 (1,485)	18	*68*	718	*200*	0.12
18[2]	69 (2,029)	11	*41*	1,594	*444*	0.11
Avg.	**61 (1,801)**	**18**	***68***	**944**	***263***	**0.12**
1. Thermosiphon in collector pipe loop. 2. Thermosiphon in space heating hydronic loop.						

5.6. 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 9). The results are mixed and inconclusive in regards to recommendations of backup water heater fuel source for ICS solar systems.

TABLE 9 – 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*	689	*192*
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*	9,603	*2,677*
19[1] (C2)	88.0	*2,580*	630	*176*
D	99.1	*2,903*	992	*277*
E	62.7	*1,837*	963	*269*
1. Gas water heater				

6. CONCLUSIONS

Many of the systems in the study operated at an annual solar fraction of more than 0.50, surpassing the goals of the Civano Energy Code, on the other hand, several did not. It was determined that long pipe lengths between the solar collector and water heater can almost 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 use 1,350% more non-solar energy per gallon (liter) of water than a properly installed and operated ICS solar DHW system and 550% more than a conventional DHW system (5). An "on demand" hot water recirculation system had no noticeable impact on energy use.

7. NOMENCLATURE

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

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