SHOULD ELECTRIC STORAGE WATER HEATERS BE THE PREFERRED BACKUP FOR SOLAR WATER HEATING SYSTEMS IN ZERO ENERGY HOMES?

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ABSTRACT

This paper reports a detailed study of residential solar water heating (SWH) in seven U.S. Sunbelt locations. TRNSYS computer model performance projections from the Solar Rating and Certification Corporation (SRCC) website were combined with local utility rate structures and fuel CO_2 content to evaluate economic and greenhouse gas emissions. As expected, in all but a few isolated cases, gas storage backup water heaters had lower operating costs than electric water heaters.

As with the economic analyses, electric storage backup water heaters were found to be superior to gas in only a few situations for CO_2 emissions basis as well. No situation was found where electric backup offered lower CO_2 emissions *and* lower operating costs. However, if a single tank electric backup system is substituted for a dual tank gas backup SWH system, then *both* CO_2 emissions and operating costs are lower in San Diego, which is an important market because of the SWH pilot incentive program begun in 2007. This pattern was also found in Phoenix.

1. INTRODUCTION

If natural gas is available on-site, most SWH system designers and installers select gas water heaters for backup water heating. For typical SWH systems, gas storage water heating is assumed to be more cost-effective than electric storage water heating regardless of utility rate structures. For further energy savings, tankless water heaters are becoming more common in SWH backup applications.

With increasing interest in climate change, CO_2 emissions are surpassing economic savings as the primary metric for evaluating the performance of SWH systems, either for SWH incentive programs or “zero energy” home design. Although the amount of CO_2 generated by burning a therm of natural gas is a constant, the CO_2 embedded in a kilowatt-hour (kWh) of electricity varies by generation type. For this study, state or regional average CO_2/kWh values available on the DOE website were used. Electricity was found to have 214% to 345% the CO_2 content of an equivalent amount of natural gas.

Water heaters are a significant source of greenhouse gas emissions. Many states have set lofty targets for reductions in CO_2 emissions that will be difficult or impossible to reach without widespread deployment of SWH or advanced water heating technologies. Reducing CO_2 emissions from water heaters by 50% is feasible using existing SWH and efficient gas water heating technologies. A similar reduction in automobile emissions will require costly development of new technologies and fuel distribution systems. The low operating cost of standard-efficiency gas water heaters (about $250/year for the typical household) will require substantial incentives for these technologies to have a broad impact. Incentive programs should consider each state’s mix of gas and electric water heaters and CO_2 content of local electricity to have the greatest reduction in greenhouse gas emissions.

Water heating represents about 12% of residential energy demand.[1] For all-electric homes, water heating accounts for about 20% of annual electricity consumption.[2] In the Sunbelt locations that account for the bulk of SWH installations, the percentage is probably higher due to lower total energy consumption because of reduced space heating demands. Although still important, economic concerns are supplanted by performance demands as the primary consideration in ZEH water heating system design. Standby losses are 6-25% of annual water heating energy consumption for typical houses. When used as backup for the large SWH systems employed in some ZEHs, standby losses will exceed 50% of the annual backup water heating energy consumption. In extreme cases, the lower tank losses of an electric water heater may offset the higher CO_2 content of electricity.

Further complicating matters is the evolving definition of zero energy homes. The simplest definition uses a single energy meter that ends the year at the same place where it began. The elegance and defensibility of this argument appeal to many, including John Reynolds, the chair of ASES. This definition does not allow any natural gas use because only an electrical meter can be moved backwards by feeding on-site energy back into the distribution system. A more pragmatic definition preferred by home builders and some at DOE and NREL is to allow for reduced natural gas consumption which must be offset by electricity generated on-site in excess of the electricity consumed. The CO_2 content of the local utility electricity mix is used to calculate fuel switching ratios. This definition is hindered because most electrical utilities will not allow negative annual bills, meaning that the excess electricity generated has zero economic value to the homeowner.

Although not evaluated as part of this study, green power purchase agreements (PPAs) can lower the carbon content of electricity to near zero. When used in conjunction with green PPAs, electric backup becomes the clear choice in all situations to minimize CO_2 emissions, despite operating costs that can be several times higher than gas. One danger is that PPAs can be terminated at any time, resulting in higher CO_2 emissions than anticipated.

Seven U.S. Sunbelt locations were chosen for this study. Roughly half of all U.S. SWH installations take place in Hawaii, where natural gas in not available. Of the remaining U.S. installations, about 80% are in the Sunbelt states of California, Arizona, and Florida. Northern U.S. SWH installations often include space heating, making this analysis more difficult. Particular emphasis was placed on California, which has a wide variety of climate zones and electricity with a lower than average carbon content. California also recently passed a $35 million SWH incentive program. The study evaluated four California climate zones: CZ03 (Bay Area), CZ07 (San Diego), CZ12 (Sacramento), and CZ15 (Palm Springs). Phoenix, AZ; Austin, TX; and Daytona Beach, FL were also chosen because of their active solar water heating markets.

2. BACKUP WATER HEATING TECHNOLOGIES

Despite higher operating costs, electric storage water heaters have several advantages over gas storage water heaters. They are simpler, have lower first costs, are easier and cheaper to install, and have less risk of fire or explosion. But the primary advantage of electric water heaters is higher operating efficiency. Electric storage water heaters in the standard residential sizes of 30 to 50 gallons have operating efficiencies of 91% to 94%. (Water heaters are rated with an Energy Factor which is roughly equivalent to operating efficiency.) Because electric heating elements have 100% conversion efficiency, all operating losses are due to heat loss to the ambient through the tank walls. Without a flame to worry about, electric water heaters have a wider variety of material options such as plastics or fiberglass. An excellent example is the Rheem Marathon electric water heater, which has a corrosion-proof tank made from seamless, blow-molded polybutene.[3]

Unfortunately, the higher operating efficiency of electric water heaters is offset by the relatively low conversion efficiency of fossil fuel electrical generation. Typical natural gas power plants have an efficiency of about 33% when transmission losses are included, making the total fuel-to-hot-water efficiency only 31%. This is reflected in operating costs and CO_2 emissions of electric water heaters, which are roughly double those of standard-efficiency gas storage water heaters. (As with green PPAs, cogeneration plants can be a “game changer” but the demand for their waste heat limits broad use.)

Electric water heaters cost only about $250 in big-box retail stores. Consumer Reports estimates that they are about twice as expensive to operate as standard-efficiency gas storage water heaters (in non-solar applications).[4] Current utility tariffs for the locations studied here indicate that electric water heater annual operating costs are 5% to 360% higher than standard-efficiency gas storage water heaters.

In contrast to electric water heaters, typical residential gas storage water heaters are only 60% efficient, due in roughly equal amounts to conversion inefficiency and tank losses. Tank losses for gas storage water heaters are greater due to the center flue, which creates a second heat loss path. Flue dampers and powered exhaust water heaters have had only limited market penetration due to high cost and installation complexity. Tankless water heaters obviously eliminate tank losses, but retain a typical gas burner conversion efficiency of about 82%. Some existing gas-fired products, including high-end residential gas water heaters, have conversion efficiencies (AFUE) as high as 92%. However, conversion efficiencies greater than 80% result in condensation in the flue, necessitating stainless steel flue and chimney construction. High costs of condensing units have limited sales, while sales of tankless gas water heaters are growing; it is not clear whether this trend is due to energy savings or the appeal of "endless" hot water.

The primary market barrier to more efficient gas water heaters is first cost. While electric water heaters are near their efficiency limit, gas water heating technologies can further improve efficiencies despite limited market success so far. Standard-efficiency gas water heaters with glass-lined steel tanks cost about $350 at chain retail stores, while advanced gas water heaters cost from $800 to $3000 or more. A recent R&D project funded by the California Energy Commission was unable to convince any major water heater manufacturer to develop a more efficient low-cost gas storage water heater, despite the ongoing threat of significant NO_X emission restrictions from the South Coast Air Quality Management District. An additional market barrier is that most water heaters are sold for emergency replacements. A representative of a major water heater manufacturer estimates that 80% of water heater sales are for emergency replacement.

Because tankless gas water heaters are included in only a small number of systems certified by the Solar Rating and Certification Corporation (SRCC), there are insufficient data to extend this comparison to tankless gas water heaters. However, from limited SRCC data, tankless gas water heaters appear superior to electric storage water heaters in all circumstances.

(Tankless electric water heaters and heat pump water heaters were not considered in this paper. Large numbers of tankless electric water heaters would likely cause significant strain on electrical distribution systems. Heat pump water heaters have had only limited market penetration. Also, SRCC has not certified a SWH system with a tankless electric or heat pump water heater.)

3. ECONOMIC AND EMISSIONS INPUTS

Energy prices and CO_2 content for the seven selected locations studied are shown in Tables 1 and 2. Although most ZEHs will use time of use (TOU) rates to maximize PV economics, TOU rates were not used in this analysis because SRCC provides only a single value for annual energy savings, with no indication of how electric water heater use was distributed. Where applicable, second tier prices were used.

TABLE 1: GAS PRICES AND CO_2 CONTENT

<table>
<tr><th>Location</th><th>Gas Utility</th><th>Gas Price ($/therm)</th><th>CO₂ content (lb/therm)</th></tr>
<tr><td>CZ03 (Bay Area)</td><td>Pacific Gas and Electric</td><td>$1.36831[5]</td><td rowspan="7">12.0593[6]</td></tr>
<tr><td>CZ07 (San Diego)</td><td>San Diego Gas and Electric</td><td>$1.48319[7]</td></tr>
<tr><td>CZ12 (Sacramento)</td><td>Pacific Gas and Electric</td><td>$1.36831[5]</td></tr>
<tr><td>CZ15 (Palm Springs)</td><td>Southern California Gas</td><td>$1.07612[8]</td></tr>
<tr><td>Phoenix, AZ</td><td>Southwest Gas</td><td>$1.51474[9]</td></tr>
<tr><td>Austin, TX</td><td>Southwest Gas</td><td>$1.15950[10]</td></tr>
<tr><td>Daytona Beach, FL</td><td>Florida Public Utilities Co.</td><td>$1.15950[11]</td></tr>
</table>

TABLE 2: ELECTRICITY PRICES AND CO_2 CONTENT

<table>
<tr><th>Location</th><th>Electric Utility</th><th>Electricity Price ($/kWh)</th><th>CO₂ content (lb/kWh)</th></tr>
<tr><td>CZ03 (Bay Area)</td><td>Pacific Gas and Electric</td><td>$0.22609[12]</td><td rowspan="4">0.879[13]</td></tr>
<tr><td>CZ07 (San Diego)</td><td>San Diego Gas and Electric</td><td>$0.13452[14]</td></tr>
<tr><td>CZ12 (Sacramento)</td><td>Sacramento Municipal Utility District</td><td>$0.1413[15]</td></tr>
<tr><td>CZ15 (Palm Springs)</td><td>Southern California Edison</td><td>$0.24609[16]</td></tr>
<tr><td>Phoenix, AZ</td><td>Arizona Public Service</td><td>$0.12175[17]</td><td>1.254[13]</td></tr>
<tr><td>Austin, TX</td><td>Austin Energy</td><td>$0.0602[18]</td><td>1.421[13]</td></tr>
<tr><td>Daytona Beach, FL</td><td>Florida Power and Light</td><td>$0.04435[19]</td><td>1.328[13]</td></tr>
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4. CALCULATIONS

As part of the OG-300 SWH system certification, SRCC develops a TRNSYS computer model for each system that is calibrated using laboratory test data. This computer model is used to establish the Solar Energy Factor (SEF) for each system. The SEF is a valuable performance rating useful for comparing performance between solar systems, but it offers little indication of energy savings. The SRCC runs the computer model with TMY weather data files for 89 different U.S. cities to generate estimated annual energy savings. These data, along with the certification sheet for each system including plumbing schematic, are available in PDF format on the SRCC website.[20] Each TRNSYS certification number covers a solar/backup water heater combination, so one solar water heater may have certifications with electric storage, gas storage and gas tankless backup heaters. Certifications are generally grouped with varying collector and storage tank sizes. The TRNSYS model uses the operating conditions and weather data shown in Table 3.

TABLE 3: SRCC MODEL OPERATING CONDITIONS

Condition	Value
Hot water load	64.3 gallons (243 liters) per day drawn throughout the day with the maximum loads occurring at 8 AM and 8 PM
Water mains temperature	Varied monthly using local data
Collector orientation	Facing south at a tilt of 22.6°
Distance from collector to tank	25 feet (7.6 meters) pipe length (each way), 16 feet (4.9 meters) vertical rise
Backup heater setpoint	125°F (51.7°C)
Weather conditions	TMY data file
Air temperature around indoor tanks	$T_{AIR} + [(72-T_{AIR})/3]$
Electric water heater	50 gallon, EF = 0.90
Gas water heater	50 gallon, EF = 0.60

For this analysis, the four most common SRCC certified SWH systems were selected, with representative systems identified for each system type, as shown in Table 4.

TABLE 4: SWH SYSTEM TYPE AND MODELS

System Type	OG-300 Cert. #	Backup	Description
Drainback Active	2001007C	Electric Storage	Six Rivers Solar Trendsetter (210 gallon) with four SP-40 collectors
	2001002C	Gas storage	
Thermosiphon	2001010E	Integral electric	Solahart indirect thermosiphon with three J panels
	2001013E	Separate electric storage	
	2001016E	Gas storage	
Closed-Loop Active	1993001H	Single tank electric	SunEarth Solaray indirect with two EC-32 collectors
	1996001F	Two tank electric	
	2001001F	Two tank gas	
Progressive Tube ICS	1992011F	Electric storage	SunEarth Copperheart CP-40 (40 gallon)
	2001002C	Gas storage	
	2002006C	Gas tankless	

With the exception of integral collector + storage (ICS) systems which have sufficient thermal mass to survive light freezes, Hawaii is the only U.S. climate suitable for direct SWH systems, which circulate pressurized potable water through the collectors, making them highly susceptible to freeze damage. Without natural gas supplies, Hawaii and direct SWH systems were beyond the scope of this study.

Annual performance estimates were taken from the PDF files on the SRCC website and entered into a spreadsheet. Many more systems were evaluated that those shown here to identify broad trends and focus on the most relevant systems, with an emphasis on larger SWH systems that would be considered for ZEHs. Progressive tube ICS systems were included in the study because they have the most certifications with gas tankless water heaters.

Annual energy savings for OG-300 systems that include an electric backup heater are given in kWh, and in therms for systems that include a gas water heater. To simplify comparisons, all natural gas data were converted to kWh. The following conversions were used in this study.

1 therm = 29.308 kWh
1 therm = 100,000 BTU
1 therm = 105,500,000 joules
1 therm = 100 ft^3 natural gas
1 metric ton = 2205 lb

5. BASELINE PERFORMANCE (NO SOLAR)

For each location, SRCC includes baseline energy consumption for electric and gas storage water heaters. Tankless water heaters were estimated to save 45 therms per year. Based on these input energy amounts (in kWh or kWh-equivalent), CO_2 emissions (on-site for gas, at power plant for electric) and annual operating costs were calculated. The results are shown in figure 1.

CO_2 emissions are highest where coal power plants dominate the energy mix; the coal scenarios typically also result in the lowest electricity prices. Examples are Austin and Daytona Beach, with the highest CO_2 emissions (even with relatively low water heating loads) but the lowest operating costs. Without SWH in Austin, an electric water heater costs only about 5% more to operated than a gas storage water heater. Even though Palm Springs has the lowest water heating loads due to high water main temperatures (less load) and high ambient temperatures (less tank losses), it has the second highest electric water heater operating costs in this study due to the highest electricity prices. Electric water heaters in California generate 26% less CO_2 than the average of the three other locations due to a cleaner fuel mix that includes mostly natural gas fired power plants along with some hydro power, despite 13% higher water heating loads than the other three locations. Electric water heaters generate 46% to 137% more CO_2 emissions than gas storage water heaters, while consuming about 30% less input energy. Gas tankless water heaters have an average of 24% less CO_2 emissions than gas storage water heaters, and save an average of \$52/year, in line with Consumer Reports estimate of \$50/year.[21]

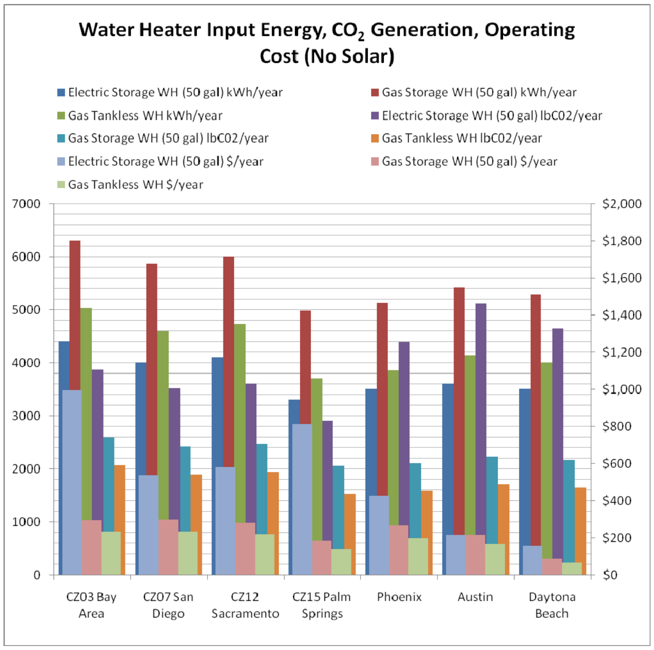

Fig. 1

6. SOLAR FRACTIONS

Solar fraction (SF) represents the percentage of the total water heating load that is satisfied with the SWH system. Although 100% SF is theoretically possible, in reality it is almost impossible to attain without massive thermal storage to "glide" through the coldest and/or cloudiest winter weather without using the backup heat source. Such a large storage tank will require a very large collector array to offset tank losses. SF values for this analysis are shown in figures 2 and 3.

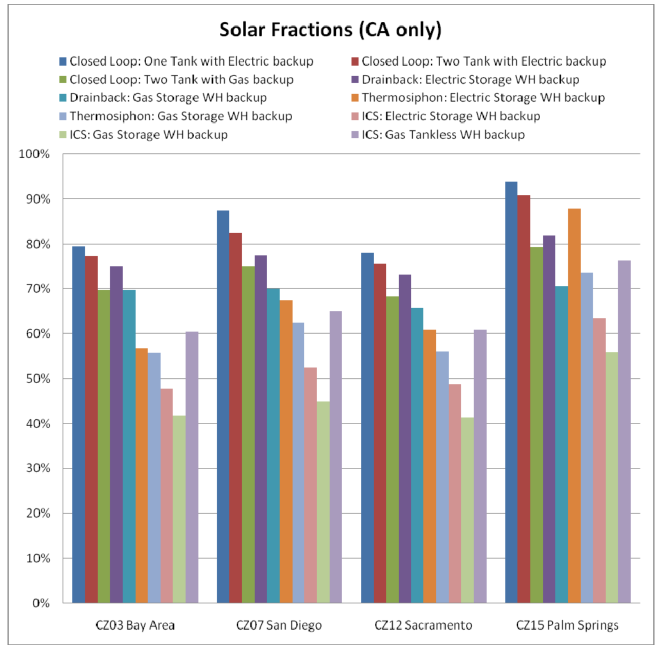

Fig. 2

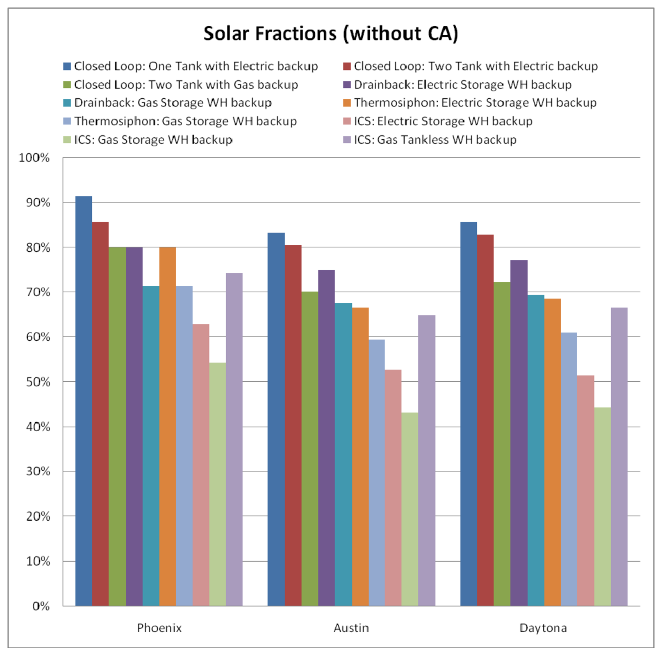

Fig. 3

The highest SF in this study is 94% for the single tank closed loop active system in Palm Springs with an electric backup water heater. Surprisingly, the drainback active system is about 11 percentage points lower than the closed loop system, despite having 160 ft^2 of collector compared to only 64 ft^2, and 210 gallons of storage compared to only 80 gallons. As expected, ICS systems have the lowest SF, but did reasonably well in Phoenix, where they are popular.

Gas storage water heaters show about 8 percentage points lower SF than electric water heaters. Gas tankless water SF is 13 percentage points higher than electric for the ICS system.

7. DRAINBACK RESULTS

Large unpressurized drainback systems such as the one modeled here are often used in high performance homes because the storage water can be circulated directly through hydronic space heating systems.

The result of the analysis for the Trendsetter 210 gallon Six River Solar tank with four SunEarth SP-40 4' x 10' collectors is shown in figure 4. In Palm Springs, the electric backup water heater generates 13% less CO_2 than the gas storage water heater, but costs 174% more to operate. For all other locations, the electric water heater generates more CO_2 than the gas storage water heater. Despite generating 77% more CO_2, the electric water heater costs 22% less to operate in Austin. In all other locations the gas storage water heater has lower operating costs.

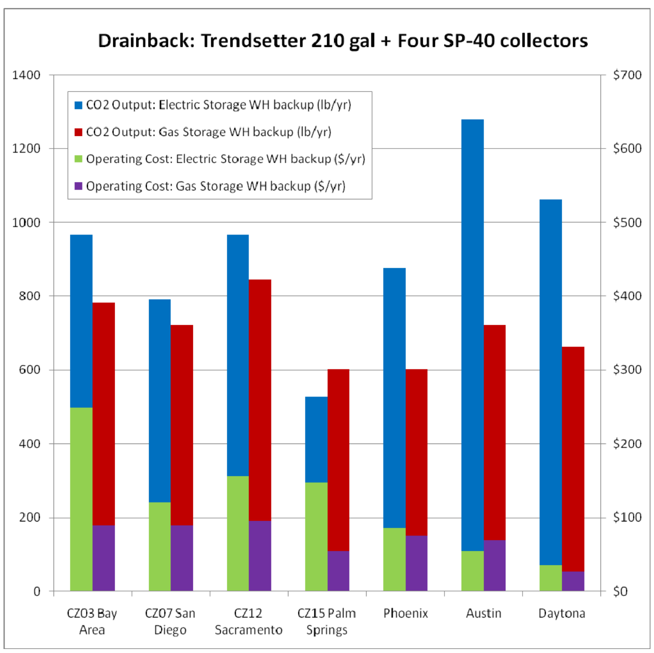

Fig. 4

8. THERMOSIPHON RESULTS

Thermosiphon SWH systems are popular throughout the Sunbelt because they are less complicated to install and maintain than active systems, yet nearly match their performance. Thermosiphons are passive and do not require indoor floor space, but they are generally considered to be the least physically attractive type of SWH system.

The results of the analysis for the Solahart thermosiphon using three J panels are shown in Figure 5. Once again, Palm Springs is the only location where the electric backup water heater generated lower CO_2 emissions than the gas storage water heater, this time by only 3%, but costing 205% more to operate.

Thermosiphon systems can include a backup electric heating element in the storage tank to eliminate the need for any indoor water heating equipment. At first glance, eliminating the indoor backup tank should result in lower electricity consumption due to lower tank losses. But this configuration requires that the outdoor thermosiphon tank maintain the desired setpoint, resulting in higher tank losses, particularly in the winter when the thermosiphon tank is normally below the setpoint. Based on the SRCC projections, there is no clear pattern suggesting one preferential configuration for electric backup. In San Diego, Austin, and Daytona Beach, both systems had identical electric consumption. In the Bay Area and Sacramento, the integral heater had higher electricity consumption, likely caused by the lowest winter ambient temperatures. In Phoenix and Palm Springs, the integral system used less electricity. In Palm Springs, the integral system generated 45% less CO2 than the gas backup, but still cost 103% more to operate.

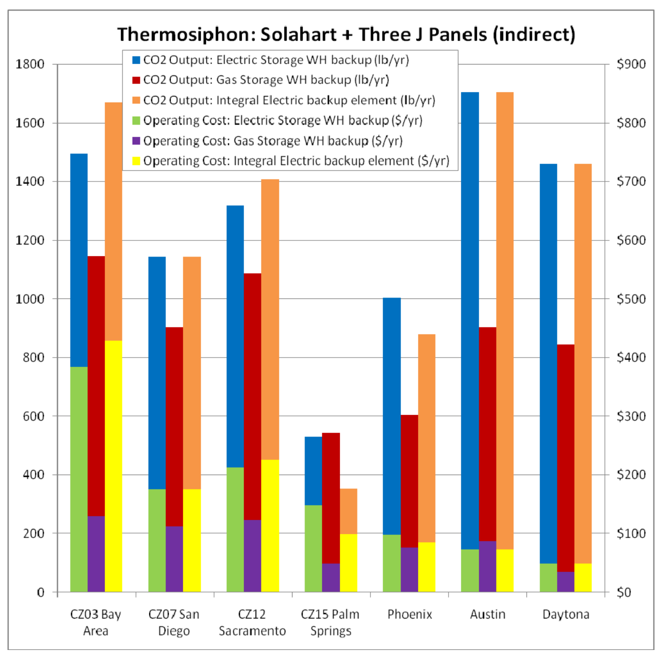

Fig. 5

9. CLOSED LOOP RESULTS

Closed loop active SWH systems are installed throughout the U.S. because of excellent performance and the ability of the propylene glycol heat transfer fluid to survive deep freezes. They also require the most maintenance.

As with the drainback and thermosiphon systems, CO_2 emissions and operating costs are presented in figure 8 using the traditional arrangement where the SWH pre-heats water before it enters the electric or gas storage backup water heater. In addition, closed loop systems can have a single 80 gallon tank with a single integral electric heating element, similar to an electric water heater using only the upper element. A wrap-around heat exchanger transfers solar energy to the lower half of the pressurized storage tank. The single tank approach reduces total storage and may result in insufficient hot water for large households, but should be similar to a 40 gallon electric water heater (albeit with a slower recovery rate). One and two tank closed loop active SWH systems are shown in figures 6 and 7.

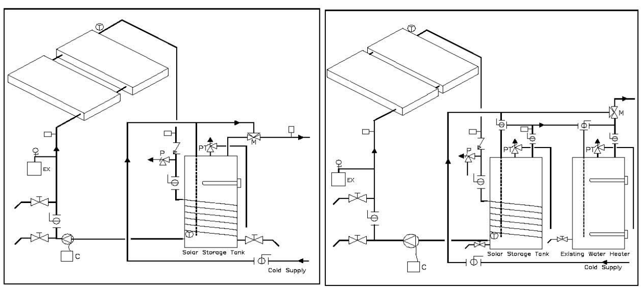

Fig. 6 and 7

As the highest performance SWH systems evaluated, closed loop systems should have the most instances where an electric backup water heater generates less CO_2 emissions than a gas storage water heater. Unfortunately, Palm Spring was again found to be the only location where this occurs, this time by 38% with 96% higher operating costs.

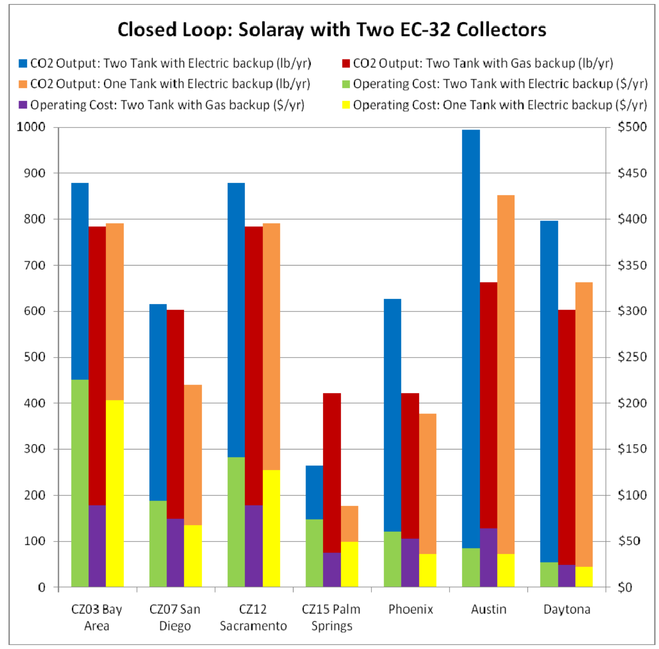

Fig. 8

However, when the single tank closed loop system with integral electric backup is compared to the two tank system with gas storage backup, San Diego also has lower CO_2 emissions for the electric backup. *Furthermore, this 27% reduction in CO_2 emissions includes 9% lower operating costs.* This conclusion may be particularly relevant to the SWH pilot program begun in San Diego in 2007 as part of the California Solar Initiative administered by the California Center for Sustainable Energy. Comparing these two configuration, Phoenix also has lower CO2 emission (by 11%) *and* operating costs (by 31%) for the single tank system.

9. ICS RESULTS

ICS systems were popular in the 1990s because they were affordable, passive, and simple to install. However, because each 40 gal. ICS unit contains about 180 lbs. of copper, wholesale prices for ICS systems have tripled since the 1990s and production rates have fallen. ICS systems were included in this study because SunEarth has had their 40 gal. Copperheart ICS system certified with electric storage, gas storage, and gas tankless backup water heaters. The results of the analysis of ICS systems are shown in figure 9.

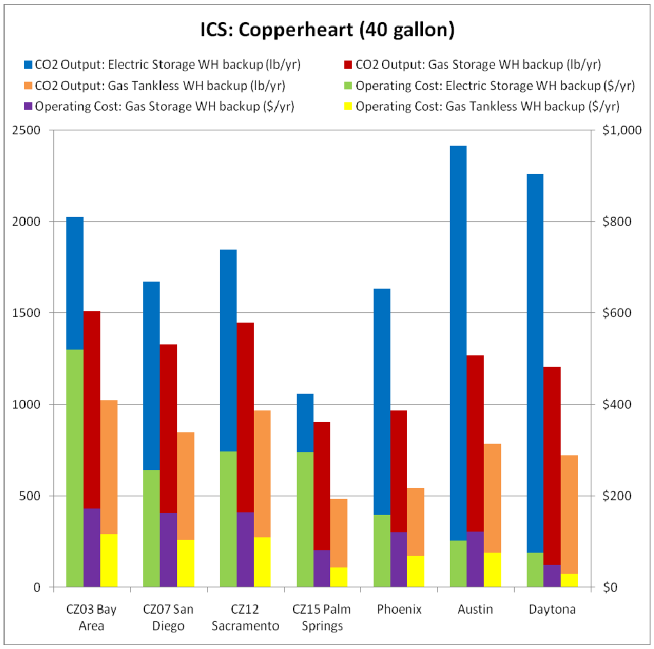

Fig. 9

Because of their low solar fractions, electric backup water heaters with ICS systems always generate more CO_2 emissions than gas storage water heaters, even in Palm Springs. Gas storage water heaters average 30% less CO_2 emissions and operating costs than electric storage water heaters in these seven locations. Tankless gas water heaters increase these savings to about 56%.

Tankless water heater sales are growing rapidly, and they are becoming more common for use with SWH systems. This analysis indicates that tankless water heaters offer the lowest CO_2 emission and operating costs of all backup water heaters used in SWH applications. However, tankless water heaters have a minimum firing rate of about 15,000 BTU/hr which can lead to fluctuating water temperature at fixtures. At 0.5 GPM, the minimum temperature rise in a tankless water heater is 60°F. For water main temperatures of 50-60°F, the 0.5 GPM minimum rise is not a problem. But if a SWH system is heating the water to 85°F, then the tankless water heater will not be able to remain below the 130°F setpoint, and will either shut down or cycle on and off. Even at 1.0 GPM the minimum temperature rise is 30°F. This may result in call-backs or complaints if customers have not been made aware of this issue before the installation. The SWH industry should work with tankless water heater manufacturers to eliminate this compatibility issue.

5. REFERENCES

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