SIMULATED PERFORMANCE OF SOLAR DOMESTIC HOT WATER TECHNOLOGIES IN NEW YORK STATE

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ABSTRACT

In this paper, the performance of Solar Domestic Hot Water (SDHW) systems and baseline conventional DHW systems are simulated in thirteen regions of New York State using TRNSYS simulation software. The SDHW design factors considered in this assessment include collector type (flat plate, evacuated tube, unglazed building-integrated) and tank configuration (single tank, two tank, external heat exchanger, SDHW tank with instantaneous water heater).

SDHW system performance is evaluated against conventional DHW system performance in terms of energy production and solar fraction.

The results are rendered into color geographical maps of New York State, where the different colors represent different values of the solar fraction for the selected system.

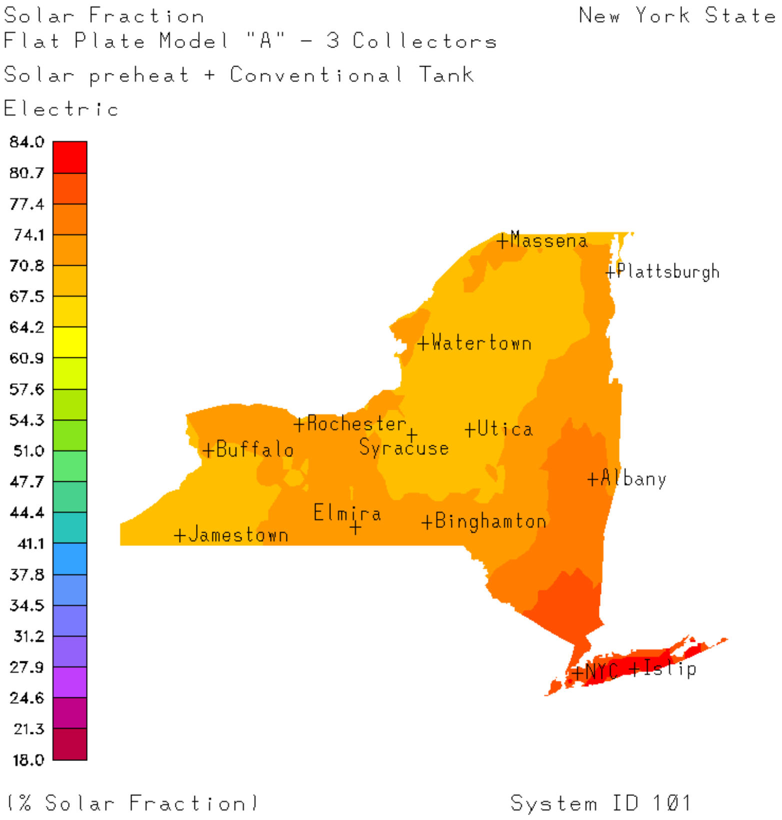

Figure 1 Geographical rendering of Solar Fraction for System ID 101

INTRODUCTION

In 2001, a total of 2 billion kWh of electricity, 2.15 billion cubic meters of natural gas and 1.12 billion liters of fuel oil were used to heat water in New York households. Water heating accounted for 18% of New York State household energy consumption (Energy Information Administration, 2007). As in 2001, the vast majority of the energy currently used to heat water in homes is derived from fossil fuels, either by burning them directly or by using electricity (in New York State, electricity itself is derived in majority from burning fossil fuels.

The research described herein will help to identify the most promising solar DHW technologies across different regions of New York State. Given that solar fractions greater than 50% are possible with SDHW, this technology has the potential to substantially reduce dependence on fossil fuels for DHW, thereby reducing greenhouse gas emissions and other harmful results of fossil fuel use.

NOMENCLATURE

Each system design in this paper is referred to by a three digit number. The first digit or "hundreds" place, refers to the collector type, the second digit or "tens" place refers to the tank type, and the third digit or "ones" place refers to the auxiliary fuel type. This nomenclature is defined in Table 1 below.

Table 1 System Design Nomenclature

DIGIT	HUNDREDS	TENS	ONES
	COLLECTOR TYPE	**TANK TYPE**	**FUEL TYPE**
0	Baseline	Solar preheat tank + 40 gal (151 L) conventional tank	Natural Gas
1	Flat Plate Model "A" - 3 Collectors	Solar preheat tank + Instantaneous (tankless) heater	Electric
2	Evacuated Tube Model "A" - 24 Evacuated Tubes	Solar preheat tank with External Heat Exchanger + 40 gal (151 L) Conventional Tank	Propane
3	Evacuated Tube Model "B" - 24 Evacuated Tubes	80 gal (303 L) Conventional Tank with External Heat Exchanger	Oil
4	N/A	Double Heat Exchanger Tank	
5	Flat Plate Model "B" - 2 Collectors		
6	Evacuated Tube Model "C" - 24 Evacuated Tubes		
7	600 Square Feet Building Integrated collector (56 m^2)		

For example, the Flat Plate Model "A" collector system with double heat exchanger tank and fueled by an oil boiler would have a System ID of 143.

METHODOLOGY

Description of Model New York State Home

Systems were designed for a typical New York State single family home with the following characteristics: 1) four occupants; 2) basement and attic; 3) two stories tall; 4) sloped roof pitched at 30 degrees towards south; and 5) heating and hot water systems located in basement. Into this home are introduced the following variables:

- Heating system: separate from DHW system (e.g. furnace) or integrated with DHW system (e.g. boiler)
- Solar energy storage in one and/or two tank arrangements

The energy consumption of the whole house is not simulated, rather only the SDHW systems and energy usage related to hot water consumption is simulated.

Hot Water Consumption

It was assumed that the hourly DHW usage in the household conforms to the ASHRAE typical family's usage, as shown in Figure 2:

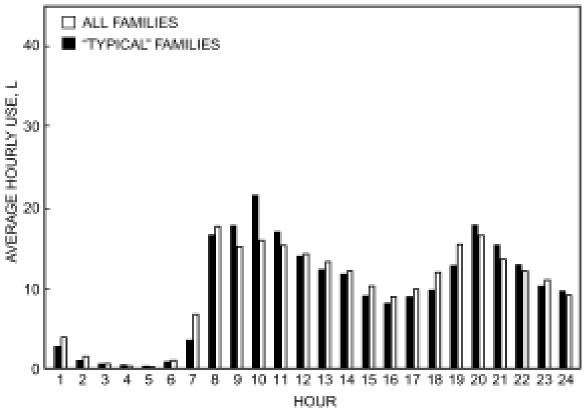

Figure 2 "Typical" Family DHW Use (ASHRAE 2003)

Solar Domestic Hot Water System Design Factors

Complete system designs were developed for the twenty-eight SDHW systems modeled in the assessment. These system designs were chosen by manufacturers as those most cost-effective for the typical New York State home outlined above. Not every system is designed to be the same size – rather some manufacturers suggested that a smaller solar

Table 2 Collector and System Properties

Sys. ID	Collector Type	Net Aperture Area (m^2)	Delta T (off/on) (ºC)	Pumping Rate (L/s)
1xx	Flat A	6.42	11.1/13.3	0.095
2xx	Evac A	5.43	10.3/14.7	0.095
3xx	Evac B	5.45	10.3/14.7	0.095
5xx	Flat B	4.59	7.8/15	0.095
6xx	Evac C	3.75	10.3/14.7	0.095
7xx	Bldg Int	55.74	11.1/---	0.158
Sys. ID	**Collector Low Limit (ºC)**	**Tank High Limit (ºC)**	**Tank 1 Volume (gal)**	**Tank 1 Volume (L)**
1xx	N/A	76.7	105	398
2xx	N/A	79.4	105	398
3xx	N/A	79.4	80	303
5xx	26.7	71.1	80	303
6xx	N/A	79.4	80	303
7xx	N/A	N/A	80	303

fraction was more desirable as the system would be less expensive to install.

The systems analyzed have variations in solar collector type, tank type & arrangement, and fuel type.

The collector types analyzed include: Flat Plate Glazed Collectors, Evacuated Tube, and Building Integrated/Unglazed, as shown in Table 2.

The systems analyzed include both one and two tank arrangements, as well as instantaneous heaters, as shown in Figures 3,4,5,6,and 7.

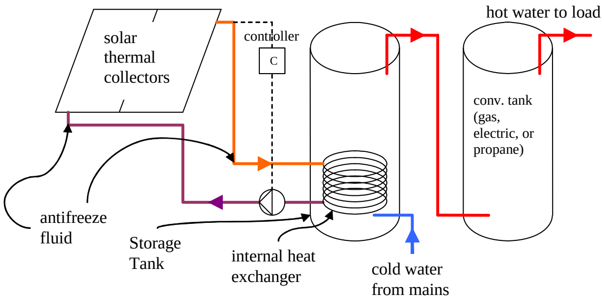

Figure 3 Tank Design x0x - Solar preheat tank + Conventional tank

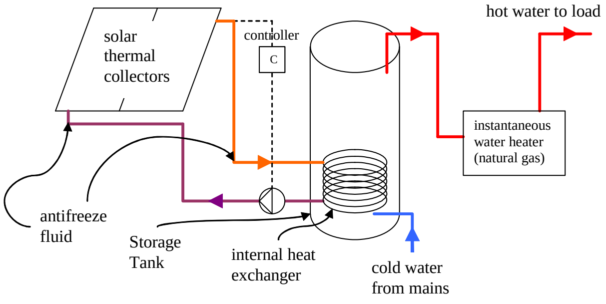

Figure 4 Tank Design x1x - Solar preheat tank + Instantaneous (tankless) heater

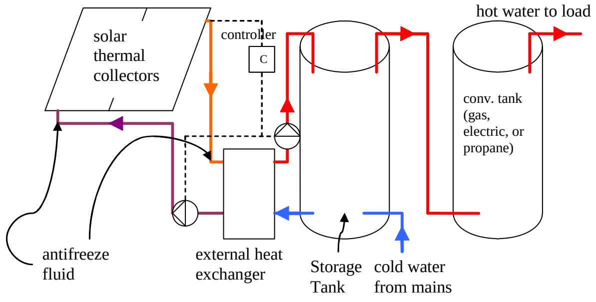

Figure 5 Tank Design x2x - Solar preheat tank with External Heat Exchanger + Conventional Tank

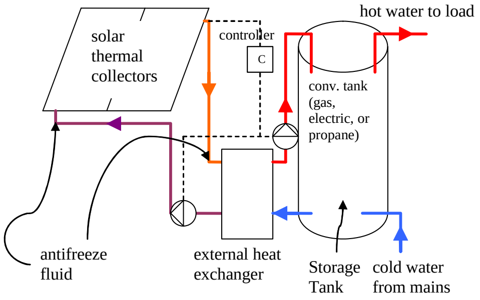

Figure 6 Tank Design x3x - Conventional Tank with External Heat Exchanger

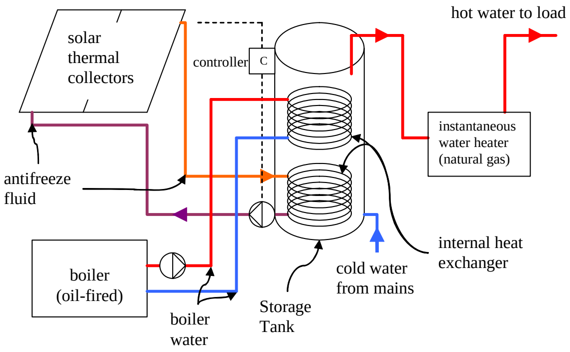

Figure 7 Tank Design x4x - Double Heat Exchanger Tank

The four fuel types analyzed – natural gas (xx0), electricity (xx1), propane (xx2), and oil (xx3) – account for nearly all of the DHW fuel in the State.

DHW baseline comparison

Each SDHW system has a corresponding conventional hot water heating system baseline. Each baseline system has a tank volume and fuel type identical to that of the auxiliary tank in the associated SDHW system.

Table 3 Baseline Systems modeled in the assessment

System ID	Description
000-40/80	a conventional gas fired water heater - 40 gallon (151.4 liters) or 80 gallon (302.9 l)
001-40/80/120	a conventional electric resistance water heater – 40/80/120 gal. (151/303/454 liters)
002-40/80	a conventional propane water heater - 40 gallon (151.4 liters) or 80 gallon (302.9 l)
010	An 82.3% efficient instantaneous heater serves as the backup for this system.
043-80/105	A conventional indirect hot water tank with a single lower heat exchanger fueled by an oil boiler. 80% efficient -80 gallon (302.9 l) or 105 gallon (397.6 liters).

In the assessment, it was assumed that all heating appliances were installed according to manufacturer's instructions with no additional insulation.

Climatological Data

The climatological irradiance data used as an input to the simulations consist of TMY-2 data (NRELa, 1994) which have been adjusted to account for the high-resolution spatial distribution of solar resource derived from geostationary satellites which have recently been incorporated in the updated National Solar Radiation Data Base (NRELb, 2007). The time series generator (Perez, 2000) was used to process original TMY-2 data by adjusting each month's clearness index to reflect the recent satellite observations. The same procedure was also used to extrapolate TMY-2 data at any nearby locations. This methodology was used to generate updated TMY data at the original seven TMY-2 locations -- Albany, Binghamton, Buffalo, Massena, New York, Rochester and Syracuse -- and to generate extrapolated TMY data for Islip, Elmira, Plattsburgh, Jamestown, Watertown and Utica.

Geographical Rendition of Results

This section describes our process of graphically rendering the simulation results. The first step was to produce a gridded data file of long term averaged global irradiance data (1998-2007), spanning a region from (-80.25W, 40.25N) to (-71.05W, 45.25N), with a resolution of 0.1° (93x by 51y). For each of the 13 baseline sites in New York, the ratio Y = X/ G was computed, where X is our desired data product (solar fraction, year 1 savings, or simple payback), and G is the long term averaged global irradiance at each of the 13 sites. Ratio files for all 26 SDHW systems were generated and then input to "Surfer", a commercial software application for data gridding and 3D surface mapping. Gridded ratio data over the entire domain was generated using "Surfer's" internal Kriging algorithm. Final gridded data was calculated as the product of the gridded ratio data and the long term averaged global irradiance data at each of the domain grid points. The derived data was then input to an open source NCAR (National Center for Atmospheric Research) Graphics software application to render 2D color contour plots representing the simulated results.

Definitions

- E_aux - the fossil fuel energy used for heating, exclusive of pumping energy.
- E_disp - the difference between the baseline fossil energy and the solar system fossil energy, this is not necessarily Esol. Exclusive of pumping energy.
- SF - solar fraction, computed as the difference between the baseline fossil energy and the solar system fossil energy normalized by the baseline fossil energy. Exclusive of pumping energy.

SIMULATION MODELS

All SDHW and baseline simulations were made using TRNSYS 16. All components were modeled using the standard TRNSYS and TESS libraries (TESS, 2007). Annual simulations were performed using a one-hour time step. The climatalogical data set was created in TMY2 format using the aforementioned methodology.

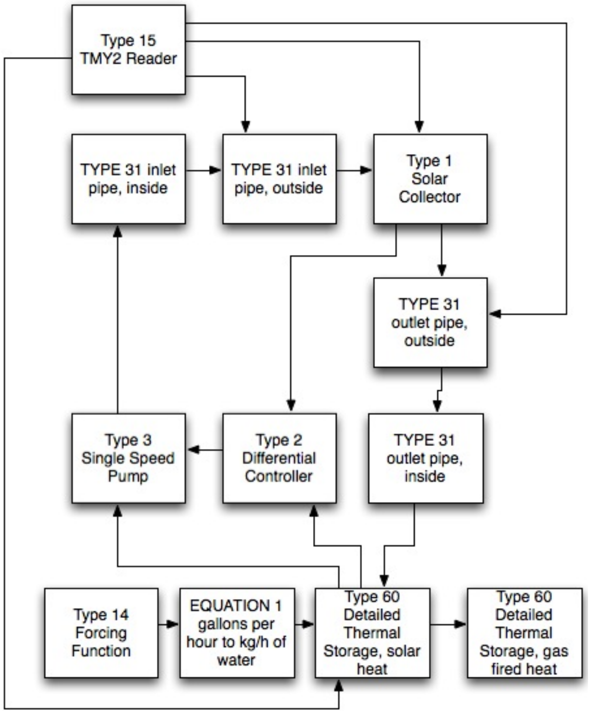

Figure 8 Typical Simulation Input (System ID 100)

Collector model

The collector model used was the Generic Type 1 for flat plate and evacuated tube collectors, which utilizes the quadratic curve of collector efficiency as a function of temperature difference between the collector and the environment and three user-specified coefficients of the function that control the performance of the collector. Performance data were taken from SRCC ratings and collectors were arranged in series.

System types

These pumped, closed-loop systems utilized the TRNSYS pump model with a controller to turn the pump on and off and used TRNSYS tank models that included heat exchanger(s).

Tank arrangements

Single tank arrangements were modeled as one TRNSYS tank with two heat exchangers. From an energy perspective, this simulation treats as equals 2HX solar tanks and single HX with upper electric element solar tanks.

Two tank arrangements used a TRNSYS tank with single heat exchanger to model a single heat exchanger solar pre-heat tank and used a TRNSYS gas or electric heated primary tank downstream from the solar pre-heat tank.

Solar tank plus instantaneous hot water heater models used a TRNSYS tank with single heat exchanger to model single heat exchanger solar pre-heat tank and used a TRNSYS instantaneous DHW type to model auxiliary heater.

Generalities

Domestic Hot Water draw profile (Type 14) used was a forcing function used to prescribe the hot water draw profile, per ASHRAE (see Figure 2). The TMY2 Reader (Type15) provided weather-related inputs to the solar collectors, including the mains water temperature model, which is used to determine the temperature of the cold water source (TESS, 2007). Detailed Thermal Storage, solar heat (Type 60) is modeled as the appropriate tank for the modeled system. Detailed Thermal Storage, gas fired heat (Type 60) is a conventional 40 gallon (151 L) gas fired water heater and was used as the auxiliary heater in all modeled two-tank arrangements with natural gas.

The Fluid Pump (Type3) model was used to simulate the circulation pumps of the SDHW systems. This component models the pumping power using a simple polynomial relationship between power and mass flow rate. In this study all pumps were based on a typical pump using 90 watts of power at a peak flow rate of 9.5 GPM (0.59 l/s). While a cubic or squared relationship is more accurate in predicting part load pumping power, due to limited information from the manufacturers, and the relatively minor role of pumping energy in the energy balance of the SDHW systems, a linear relationship was used.

The Differential Controller (Type2) used was a simple on/off controller, programmed to turn on when the differential temperature between the collectors and storage tank rose above a specified setpoint and turn off when the differential temperature became sufficiently small. The setpoint at which the controller turns on and off varied by the manufacturer's recommendations.

Inlet pipe (TYPE 31) and outlet pipe (TYPE 31) lengths were based on typical residential construction of 15 ft (4.6 m) of indoor pipe and 10 ft (3 m) of outdoor pipe. This was modeled to account for heat losses in fluid transmission between the storage tank and solar collector. The pipe was modeled as 1 inch (2.54 cm) in diameter with 1 inch (2.54 cm) of polyethylene insulation.

SIMULATION RESULTS

DHW baseline loads

Simulation results show that the baseline load varies depending on system type. As noted above, each baseline system corresponds to one or more SDHW systems – baseline systems are created to match the auxiliary tank designs of the SDHW systems.

All results are presented in "site" energy usage. Since electric resistance tanks have higher levels of insulation according to ASHRAE minimums, electric tanks are more efficient with site energy than the natural gas, propane, and oil tanks. The gas instantaneous heater is the second most efficient system, due to its low level of radiative heat loss.

The lower levels of energy usage by the electric tanks allow SDHW systems using electric backup to achieve higher levels of solar fraction than systems backed up by other fuel types.

The baseline systems were simulated at each of the 13 locations across New York State. For each given baseline system, the difference in energy usage across locales is due to the difference in "Mains Water Temperature" as simulated in TRNSYS. While presenting energy use by the baseline system (E_aux) at each location is beyond the scope of this paper, the consumption of each system at one location (Albany) is presented below in Table 4.

Table 4 Baseline System Energy Use in Albany

SYSTEM ID	Energy Usage (MJ)
000-40	25,813
000-80	28,925
001-40	17,036
001-80	17,860
001-120	18,684
002-40	25,813
002-80	28,925
010	18,583
043-105	21,023
043-80	21650

Comparison of the SDHW Systems

Simulation results of the SDHW Systems are presented in this section. Table 5 shows the annual performance of all analyzed systems in Albany, a relatively average location in the state in terms of solar radiation and temperature. E_aux represents the auxiliary energy used to heat domestic hot water in addition to solar energy. E_disp represents the amount of energy displaced by the SDHW system, and was calculated by taking the difference between SDHW E_aux and Baseline E_aux. Both E_aux and E_disp are exclusive of pumping energy.

Table 5 SDHW Annual Energy Performance in Albany

Sys ID	E_aux (MJ)	Pump Energy (MJ)		E_disp (MJ)	SF
		Sol	B		
100	9145	403		16668	65%
101	4228	401		12808	75%
102	9145	403		16668	65%
110	4766	401		13817	74%
143	7976	367	58	12990	62%
200	9443	478		16371	63%
201	4293	478		12742	75%
202	9443	478		16371	63%
243	7670	436	56	13925	64%
300	10988	379		14825	57%
301	5310	379		11725	69%
302	10988	379		14825	57%
310	6020	379		12563	68%
330	20873	981		8052	28%
331	8218	660		9643	54%
332	20873	981		8052	28%
343	8620	397	62	12969	60%
520	14169	665		11644	45%
521	8005	665		9030	53%
522	14169	665		11644	45%
530	22151	819		6775	23%
531	8248	660		9612	54%
532	22151	819		6775	23%
610	8322	414		10260	55%
641	8752	359		9932	53%
700	17370	212		8443	33%
701	10316	223		6720	39%
702	17370	212		8443	33%

Table 6 shows the performance of two-tank, natural gas fired systems at all simulated locations. When x00 systems were not offered by the manufacturer, the next most relevant system was included or the results were extrapolated – see note below Table 6. Similarly, Table 7 displays these annual solar fraction divided by the net aperture area, providing a metric for efficiency of collection. The building integrated system shows the lowest performance of 0.6% per m^2, flat plate systems (100, 520) range from 9%-10% per m^2 while an evacuated tube systems (200, 300, 600*) show 10-12% per m^2.

Table 6 Annual Solar Fraction of selected SDHW for common tank (2 tank) and fuel (natural gas) type

Location	System identification Number					
	100	200	300	520	600*	700
Albany	65%	63%	57%	45%	47%	33%
Binghamton	60%	59%	52%	41%	42%	30%
New York City	69%	67%	61%	48%	50%	33%
NYS Average	62%	61%	55%	43%	45%	32%

** Since only 641 and 610 systems are offered by the manufacturer, for purposes of levelized comparison in this table, Solar Fraction of system 600 of system was estimated by the following formula:*

$$SF_{600} = SF_{300} * SF_{610} / SF_{310} \qquad (1)$$

Table 7 Annual Solar Fraction of selected SDHW systems normalized for Net Aperture Area of Coll.

Location	System identification Number					
	100	200	300	520	600*	700
Albany	10%	12%	10%	10%	12%	0.6%
Binghamton	9%	11%	10%	9%	11%	0.5%
New York City	11%	12%	11%	10%	13%	0.6%
NYS Average	10%	11%	10%	9%	12%	0.6%

** Estimated Solar Fraction. See Table 6*

In Figure 9, the performance of the SDHW systems is presented in terms of annual solar fraction. Plots are of the same form as Figure 1 and are displayed in thumbnail format. The color scale remains the same across all maps so as to allow for ease of comparison.

Simulation Result Analysis

Immediately visible on viewing Table 6 and Figure 9 is that climate is an important factor in determining the solar fraction achieved by the system. The coastal areas of New York City and Long Island (Islip) outperform Western and Northern New York areas by 9-12% nominal, while Albany and the Hudson Valley fall between the two extremes.

In terms of efficiency per m^2, evacuated tubes are best in general. However, not system 100 and 300 perform at parity, indicating that going with an evacuated tube is not always the best bet. Given the supposed benefit of evacuated tube systems in cold climates, the similarity of performance of the systems is surprising.

Systems 1xx and 5xx are both flat-plate collectors, but 5xx exhibits much lower solar fraction. This can be attributed to a larger net aperature (collector area) as shown in Table 2. System 520 has a 28.5% smaller collector aperature and 30.4% lower solar fraction than system 100. Systems 6xx similarly realize lower solar fractions than the other evacuated tube systems 2xx and 3xx, However, system 600 (see Table 6) has a 31% smaller aperature and a 24% lower solar fraction when compared to system 200, and only a 15% lower solar fraction when compared to system 300.

Systems utilizing electricity as the auxiliary fuel source (xx1) realize the highest solar fraction. It is worth noting that these simulations results are presented in terms of site energy usage – if the analysis were instead performed in terms of “source” energy use, the electric systems (xx1) would instead be the worst performers in the chart. By this metric, electric systems typically outperform other fuel sources by roughly 10 nominal percentage points, while in fact these systems are usually the most expensive to operate.

Single tank external heat exchanger systems (x3x) vary according to the fuel source beyond the aforementioned nominal ten percent difference. Tank configurations x30 and x32 realize some of the lowest performance in Table 6 and Figure 9, while x31 systems perform relatively higher. For example, 531 outperforms 530 and 532 by 54% vs. 23% Solar Fraction, or thirty-one nominal percentage points. There is a physical reason for this. In systems 530 and 532, the position of the natural gas or propane heating element at the bottom of the tank is in close proximity to the heat exchanger carrying the solar heated antifreeze solution. Since the lower portion of the tank is already heated by natural gas or propane, there is a lower difference in temperature between the heat exchanger and the tank water, allowing much less heat transfer. On the other hand, the electric element in system 532 is located in the upper area of the tank. This allows thermal stratification across the vertical dimension of the tank. This thermal stratification in the tank leaves the lower portion of the tank at a much lower temperature, allowing for good heat exchange between the solar fluid and the tank water.

If an external heat exchanger system is to be used with a conventional natural gas or propane tank, it is clear that a two tank arrangement is preferable. This is visible by comparing the performance of 530 and 520. The thermal stratification of the preheat tank in this arrangement allows for good heat transfer in the solar preheat tank, before that water is transferred to the second tank, (see Figure 5 for tank diagram).

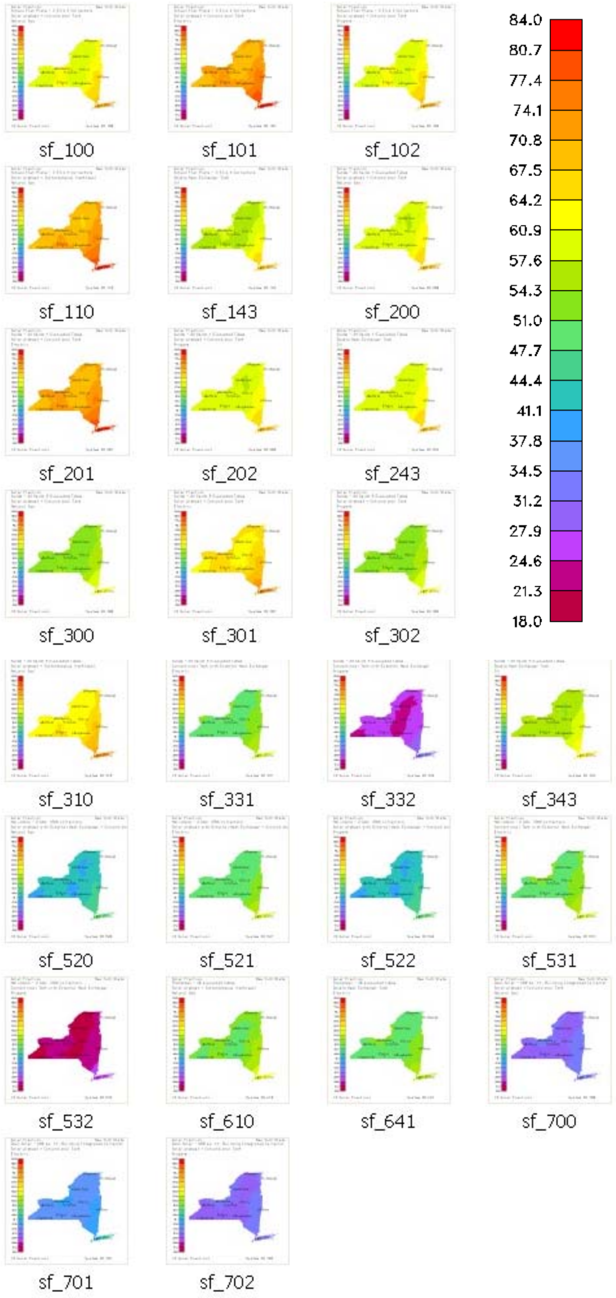

Figure 9 Solar Fraction of analyzed SDHW Systems- full size renderings at http://sdhw.brightpower.biz

If an external heat exchanger is to be used with a conventional electric tank, it appears that for the system size simulated in this assessment, consolidatation into a single tank arrangement does not harm system performance. This is visible by comparing systems 531 and 521. Again, this is because the electric element is generally located near the top of the tank, which keeps the bottom of the tank relatively cold and allows heat exchange across between the hot solar fluid and the cold tank water.

The Building Integrated/Unglazed SDHW systems (7xx) demonstrate less variability in solar fraction across the state, perhaps because they are well insulated by the roof. Flat plate and evacuated tube systems exhibit a much greater spread in solar fraction, indicating that building integrated systems may be particularly well suited for cold climates.

It is worth noting that the unglazed building-integrated collectors show the lowest performance in solar fraction but have the longest system life, which allows savings to accrue over a longer period.

Also of note is that the 3xx and 2xx evacuated tube systems are from the same manufacturer. The manufacturer touted 3xx system as the better performer, but these “premium” tubes underperformed the less expensive 2xx in this climate region.

CONCLUSION

While this analysis is limited to New York State, it can be seen that SDHW system performance varies by climate, as one would expect, but also by a combination of the interplay between collector type, tank configuration and auxiliary heating fuel. A few key conclusions:

- Evacuated tube collectors provide the best performance per m^2, flat plate the shortest payback, building integrated the longest life.
- Manufacturer specified system designs are not necessarily optimally sized; obtaining performance data specific to a given climate and system is key.
- An external heat exchanger coupled with a single fossil-fuel fired tank does not perform well.
- Similar technologies of collectors, especially with evacuated tubes, can perform quite differently.
- Unglazed building-integrated collectors have more consisent performance throughout the different climate zones analyzed herein.

This paper describes a viable, replicable method for evaluating solar DHW system performance across a number of system types. Optimal solar fraction for the State appears to be 75%, which corresponds to a summer solar fraction of 100%. Economically speaking, a solar fraction below 50% for a single family home is challenging to justify in terms of cost, due to high fixed cost and relatively low marginal cost for additional panel and tank capacity.

Economics, including installed & maintenance cost, annual and life-cycle savings, simple payback & net present value are analyzed in more detail in the full assessment which is available at http://sdhw.brightpower.biz. A browser for viewing full-size color renderings is available as well.

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