ANALYSIS OF THE ACCURACY OF USING SOLAR TANK ENERGY FACTOR FOR ESTIMATING SAVINGS IN FIELDED SOLAR HOT WATER SYSTEMS

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ABSTRACT

Utility rebates for solar hot water (SHW) systems are often based on SRCC OG300 savings ratings. Some utilities want to verify the accuracy of these ratings based on field measurements. However, energy savings—the amount of electricity and/or gas offset by the SHW system—cannot be measured directly. Savings are frequently estimated based on equations that use the solar tank's energy factors along with measures of the energy in the solar loop, the solar tank's electric element, and/or the load. We used the TRNSYS model and a SHW testbed to investigate the accuracy of these estimation methods. We modeled two popular SHW systems and computed annual energy savings from these simulations using the OG300 methodology. We applied three popular savings estimation equations to estimate savings and compared them to those measured from the simulations. Similarly, we used a testbed to run short term simulations and compared the measured savings with estimates. Our results suggest that the most accurate savings estimations are based on measured load and electric element energy rather than the energy in the solar loop.

Keywords: solar water heaters, energy factor, draw profile, energy savings, installation rebates, utility, monitoring.

1. INTRODUCTION

A number of electric utilities are interested in measuring savings from fielded solar hot water (SHW) systems. They wish to know with certainty the real impact of these systems on their grids. Essentially, they are interested in verifying that the OG300 ratings are reliable for determining how much less electricity will be needed from their grid as a result of solar energy production.

Some utilities have been exploring methods to perform this assessment, but have been thwarted by the simple fact that savings cannot be measured directly. Instead, savings, as defined by the Solar Rating Certification Corporation (SRCC), is an estimated value that represents the difference between the electrical energy consumed by a standard water heater supplying a residential hot water load and the electrical energy consumed by the electric element in a SHW tank supplying an equivalent residential load.

Naturally, in a field setting an all-electric home has either a SHW system with a solar-electric tank or a standard electric hot water tank. There is only one load to be served by only one water heating system. It is therefore impossible to concurrently measure the electrical energy consumed by different water heating systems serving that same load.

Various approaches to this problem have been explored. One approach is to monitor real SHW systems in the field over a long period of time, estimate the average annual savings, and compare the estimations with the OG300 ratings. One major problem with this approach is the uncertainty about the accuracy of the savings estimation techniques.

A second approach is to use models, such as TRNSYS, to verify the OG300 ratings for any area. But the OG300 ratings are based on TRNSYS models, so using TRNSYS models to verify similar models accomplishes little.

A third approach is to use testbeds to run simulations of SHW systems in the local area of interest. While this has some advantages over modeling because real systems are involved, there are pitfalls.

The first pitfall regards the assumptions about the test conditions. Like modeling, the testbed must be configured to simulate a real home, including the hot water draw profile. Since the number of simulations is very limited—typically only one or two per year—it is essential to use a representative load. There is uncertainty about what load is most representative for various areas of the country.

The second pitfall is that testbeds operate in real time and often for periods less than a full year. But the OG300 ratings are designed for a typical full year. Therefore, to fairly compare the testbed results to the OG300 ratings, the testbeds' data would have to be adjusted for weather—i.e., calibrated to a typical weather year for the local area—as well as for time, and there are no standard methods to do so.

The third pitfall is related to the problem with monitoring—the savings cannot be directly measured and must be inferred using estimation techniques. But there is uncertainty about the accuracy of those techniques, as we will discuss below.

In sum, we concluded that at this time there is too much doubt about critical parameters to employ field monitoring, computer modeling, or testbed testing to directly address the question about the accuracy of the OG300 ratings in any locality.

Our work directly addresses the confounding aspect of this problem. We set out to provide an assessment of the accuracy of three popular SHW energy savings estimation techniques.

2. ENERGY SAVINGS ESTIMATION METHODS

One savings estimation method is founded on measures of the energy production in a SHW system's solar loop, which contains the collector, a pump and heat exchanger. The pump forces a fluid through the collector where it collects solar heat. The fluid flows on to the electric hot water storage tank where some of the heat is extracted.

Typically, a BTU meter or equivalent device is used to measure the energy of the solar loop. It does so by measuring the temperature of the heat transfer fluid going to (inlet) and returning from (outlet) the collector along with the flow rate. The equation used by a BTU meter for computing the energy in the solar loop for a given period is:

$$Q_{solar} = Mass_{lp} * CP_{sol} * DT_{sol} \qquad (1)$$

Where Q_{solar} = energy in the solar loop, $Mass_{lp}$ = the mass of heat transfer fluid that passed through the collector, CP_{sol} = the specific heat of the heat transfer fluid, and DT_{sol} = the difference between the inlet and outlet temperature of the solar loop.

One method for estimating savings using the measured energy in the solar loop and the tank's Energy Factor (EF) is defined as follows:

$$Q_{saved} = Q_{solar} / EF \qquad (2)$$

Where Q_{saved} = net energy reduction in the home resulting from the SHW system and EF = the solar tank's energy factor.

For water heaters, EF is based on three factors: 1) the recovery efficiency, or how efficiently the heat from the energy source is transferred to the water; 2) stand-by losses, or the percentage of heat lost per hour from the stored water compared to the content of the water, and 3) cycling losses; how much energy is consumed in cycling between active mode and standby mode.

The American Society of Heating, Refrigeration and Air Conditioning Engineers developed the test methods for computing EF for residential water heaters (1). The Department of Energy adopted the method as a standard. Residential water heaters in the U.S. are tested and assigned EF ratings (2).

The average EF value for most commercially available domestic electrical water heaters is around 0.9. This EF value has become a de facto standard for many field studies of SHW because the exact EF rating for water heaters is often difficult to obtain.

Another method of estimating SHW savings is based on measured energy in the load and the electricity consumed by the electric element in the solar-electric storage tank. The equation for this method is:

$$Q_{saved} =(Mass_{lod}*CP_{lod}*DT_{load} -Q_{aux}*EF-Q_{par}*EF)/EF \qquad (3)$$

Where Q_{saved} = net energy reduction in the home resulting from the SHW system, $Mass_{lod}$ = the mass of fluid (water) in the hot water draws, CP_{lod} = the specific heat of the hot water load fluid, DT_{load} = the difference between the inlet water temp and water heater outlet temperature, Q_{aux} = the energy consumed by the backup water heating source (electric element in the solar tank), and Q_{par} = the energy consumed by any parasitic devices on the load side.

Itron recently used equations 2 and 3 to estimate SHW savings for some systems as part of a study of the field performance of SHW systems in southern California (3).

However, the most common method for estimating savings based on measures of energy in the solar loop is defined simply as an equivalence, which is identical to equation 2 with EF=1.0:

$$Q_{saved} = Q_{solar} \qquad (4)$$

There is an important difference between the estimation equations. Equation 3 bases the savings estimate on measures of the energy on the *load* side of the SHW system. Equations 2 and 4 base the energy savings estimate on measures of the energy in the solar loop, the *generation* side of the hot water system.

3. TECHNICAL APPROACH USING TRNSYS MODELS AND TESTBED SIMULATIONS

Our contribution to a solution to this problem was to address the accuracy of the savings estimation techniques. We planned to use both a TRNSYS model and a testbed to compare the measured energy savings with estimated savings using each of the three equations. Simultaneously, we planned to measure how the accuracy of each method might vary as a function of hot water load. We believed that such a sensitivity analysis might provide additional insight into the problem, which we theorized would be essential to developing appropriate next steps, ones that would more precisely address the issue of OG300 ratings accuracy.

Photo 1. UNM's Solar Hot Water Reliability Testbed

We planned two sets of sensitivity experiments, one involving the Solar Hot Water Reliability Testbed (SHWRT) at the University of NM (UNM) and a second set based on TRNSYS modeling. A picture of the SHWRT is shown in Photo 1.

The testbed is fully instrumented, including over 30 calibrated thermocouples, high quality flow sensors and pressure gauges, and a custom-designed National Instrument Virtual Instrument controller.

The testbed can operate in either pressurized or drainback mode and incorporates any one of four different types of collectors, including two with black chrome absorbers—one with a double glazing and the other with a single, another with a painted absorber with a single glazing, and a fourth being an unglazed polymer one. The loads for each test are fully programmable and well controlled. A picture of the four collectors used by the testbed is shown in Photo 2.
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Photo 2. Four different collector types that can operate with UNM's Solar Hot Water Reliability Testbed.

Our plan was to use the SHWRT to run short-term (i.e., 1-2 week) simulations of a SHW using varying hot water loads. We planned to run the SHWRT multiple times in paired configurations; one run using a solar panel (painted fin) and a parallel test immediately following using the same loads but with no solar panels operating.

In each test case the testbed carefully records the energy in the solar loop, the load and the electric element, all parameters needed by the estimation equations. Using appropriate measures from each pair of runs, we planned to compute the savings based on SRCC's method. This would stand as our measured savings for the test pair.

Then, taking appropriate data from the solar run of each test pair we planned to use the three savings equations (equations 2, 3 and 4) to estimate the savings for each pair of runs. We could then compare our measured energy savings with those estimations. In all cases we would use an EF value of 0.9, an average for electric water heating tanks.

It should be noted that in our testbed, the runs simulating a standard tank do not exactly duplicate SRCC's savings methodology. The SRCC method uses TRNSYS models to compare the electric energy consumed in a solar tank with the electricity consumed in a standard tank. A standard tank contains two electric elements, one located in the upper portion of the tank and one in the lower portion. The tank in our testbed is nearly identical to a standard tank, with the exception that it contains no bottom electric element and has a wrap-around heat exchanger in the bottom portion of the tank. There is less tank insulation in that bottom area of the tank. Thus, our savings computations are slightly biased.

In previous testing and modeling we found that savings computations based on a solar tank such as ours will be systematically biased lower by less than 5% on average. We did not believe this error to be significant for our tests, which focused on the verification of trends and sensitivities that do not depend on absolute accuracy.

We planned to populate a matrix with the test data to show the accuracy of the estimated savings versus the measured savings. The data would also show how savings are affected by variance in the load.

Our second set of sensitivity experiments involved the TRNSYS model. We planned to configure and run annual simulations of SHW systems that are popular in Phoenix; a SunSystem glazed model (TE40-80N-1) and a Fafco unglazed model (200-48SF-50E-50S). Essentially, we planned to duplicate the testing approach that we employed on the testbed, but use the TRNSYS model instead of real tests. The resulting matrix would therefore show the sensitivity of the savings estimates to changing loads as well as the accuracy of the three equations in estimating savings.

The reason for using both the testbed and the TRNSYS models is for verification of the trends. One method is based on a theoretical model and the other involves a real system. If the results from both methods demonstrate similar trends, then there would be greater confidence in the veracity of the conclusions that we might draw.

We planned to use SRCC's TRNSYS codes for the two SHW systems and run the models with Phoenix typical weather year data.[1] We sought to verify these models on our computers by duplicating the OG300 energy savings that are published for each system. This duplication, which we called the base case, would prove that our modeling platform was essentially identical to SRCC's and eliminate a potential uncertainty that could cloud the results.

The testbed activities and the TRNSYS modeling were performed simultaneously. The results are presented below.

4. FINDINGS FROM THE TRNSYS SIMULATIONS

The TRNSYS modeling was the most complex task because the configuration of the SHW system models is time consuming and tedious, requiring a great deal of attention to detail. After the models are properly configured, multiple executions with different input values are trivial.

We contacted SRCC for assistance. SRCC had already coded TRNSYS models for both of the systems that we planned to study because these models were used for the original computation of the systems' OG300 ratings. We asked for SRCC's permission to use their codes.

Eileen Pardo, Executive Director of SRCC, agreed to not only supply copies of the SHW configuration codes but she made their modeling expert, Steven Long, available to us at no cost for his consulting services.

We received the models and brought them to working order on our computers. After some manipulation and with the assistance from Steven Long, we were able to generate base case results that duplicated reasonably well the OG300 values for each system.

For example, using the SRCC standard load for the Fafco system we computed the base case energy savings to be 2169 kWh/yr. The published OG300 savings value is 2200, a difference of about 1.4%. For the SunEarth system, we computed the base case savings to be 2724 kWh/yr. The published value is 2750, a difference of less than 1%. We should also note that in each pair of runs (i.e., a simulation of a SHW tank and the corresponding one using a standard tank) the energy delivered to the tanks was essentially identical.

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[1] Typical Weather Year data are produced by the National Renewable Energy Lab. These hourly weather datasets are available for many cities and are designed for use in computer models. They contain hourly data for a one year period and these data are presumed to be typical of the weather in each city.

We believe that the small deviations in the bases case estimates were probably due to some differences in modeling platforms as well as weather data. We used TRNSYS version 17 but SRCC used TRNSYS version 16. Secondly, we used TMY3 data for our simulations but SRCC used TMY2.

We believed that the later version of the TMY data was more representative of the most recent weather patterns in Phoenix. Those two variations likely explain the small error between our computations and those of SRCC's and both we and Steve Long were satisfied with the results.

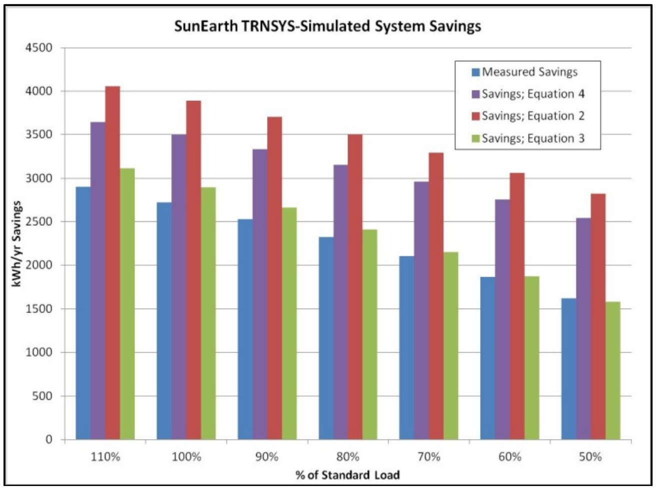

Fig. 1. Savings computed from simulations of the SunEarth system.

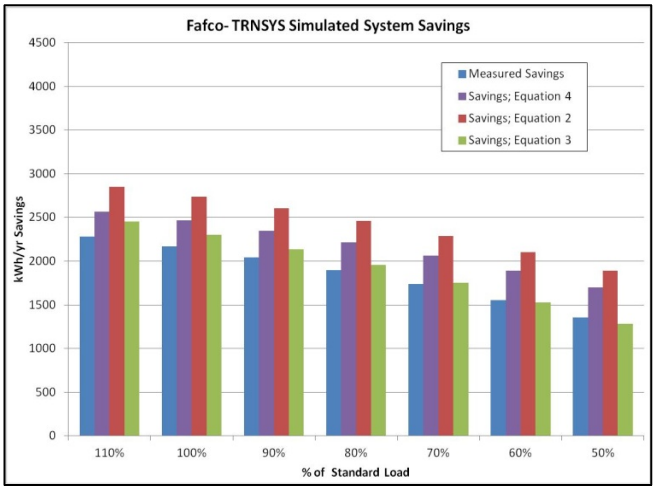

Fig. 2.Savings computed from simulations of the Fafco system.

We proceeded with the production runs and the results are presented in Figs.1 and 2.

It is obvious that equations 2 (purple bars) and 4 (red bars)—both of which use the energy in the solar loop as an input—tend to over-predict the energy savings.

The average savings estimation error from equation 3—the one using the load and electric element energy consumption as inputs—is substantially lower than the other two.

There is also a noticeable systematic bias in the error of all of the equations as a function of load. For equations 2 and 4 the prediction error is inversely proportional to the size of the load. For equation 3 the reverse is true.

A summary of the savings estimation error from each equation is presented in Table 1. The colors of the rows follow the same scheme as the bars in Figs. 1 and 2.

TABLE 1: ESTIMATION ERRORS FROM TRNSYS

AVERAGE SAVINGS ERROR (TRNSYS) (%)		
Equation #	SunEarth	Fafco
4	38	18
2	53	31
3	3	2

5. FINDINGS FROM TESTBED TESTS

The challenge with using a testbed for the kind of tests we had planned is controlling variance in ambient conditions from run to run. We tried to minimize these differences among each test pair by using a consistent approach, which is described as follows:

- Test all equipment and be ready to run.
- Wait for an extended forecast of clear weather.
- Configure the testbed with the appropriate load and collector (painted fin, single glazing).
- Begin the test in the morning before sunrise.
- Run the testbed for several days to let it stabilize thermally.
- Run the test for as long as possible before inclement weather occurred, up to 10 days.
- Terminate the test at the same time of day as when it began.
- Review the data for accuracy, which includes some quality checks such as comparisons of recorded data versus manual meters.
- Review the data and save files.

- Immediately repeat the test but without the collector in the system.
- Run the electric-only test for at least the same number of days as the solar test.
- Review the data, store them and backup files.

Each pair of tests required about six weeks to complete and some pairs were conducted for longer periods than others.

A total of ten tests were run, which produced five pairs from which savings could be computed. Three pairs of tests used loads about 10% smaller than the SRCC standard load. One test used a larger load and another used a smaller one.

Table 2 summarizes the tests that were conducted in 2012.

TABLE 2. SUMMARY OF TESTBED TESTS

Test case:	**1**	**2**	**3**	**4**	**5**
# Days in test:	5	7	8	6	5
Load/day (kWh):	10.6	8.6	8.5	8.5	7.7
Dates of tests:	3 Sep to 15 Oct	17 Jun to 1 Aug	1 Mar to 1 May	2 May to 16 Jun	2 Aug to 1 Sep

The results of the tests are presented graphically in Fig. 3. The color scheme of the bars follow those of Figs. 1 and 2.

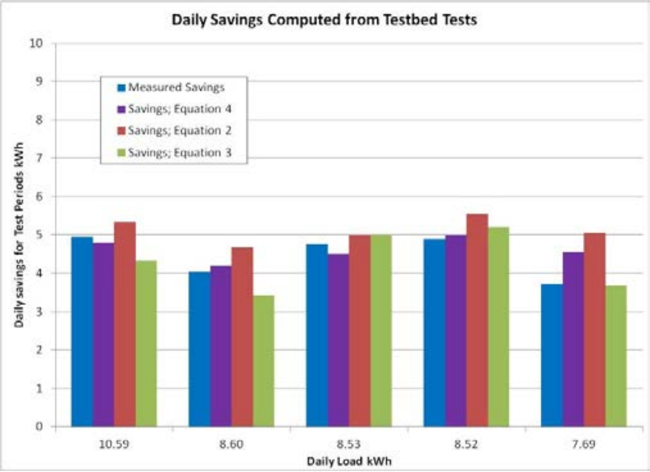

Fig. 3. Results of testbed tests.

While there is more variance with these data than those from the TRNSYS runs, the pattern is similar. Equation 2 tends to over-predict savings and equation 3 appears to produce the most accurate results.

A summary of the prediction errors from the testbed is presented in Table 3.

Columns two through six (from left) show the error in percent from using the three equations to estimate savings based on measured data taken from each test pair. The estimation equations are identified in column 1.

TABLE 3. ESTIMATION ERROR FROM TESTBED.

AVERAGE SAVINGS ERROR (TESTBED) (%)						
	UNM Testbed Test Case Number					Mean error
Eq.	1	2	3	4	5	
4	-3.2	4.1	-5.5	2.0	22.2	3.9
2	7.5	15.6	5.0	13.4	35.9	15.5
3	-12.7	-15.3	4.9	6.4	-1.2	-3.6

6. CONCLUSIONS

We conclude that equation 3, which uses only measures of the load and the tank's electric element—was more accurate than either equation 2 or 4. In other words, if in every test we had measured the hot water loads along with electric energy in the tank's electric element and applied equation 3 with an assumed EF value of 0.9, our estimates of energy savings would have been significantly closer to the real savings value than had we used either equation 2 or 4 in the traditional manner. We believe that Equation 2 is flawed for any value of EF.

Our findings suggest that the most accurate method to measure the savings from a SHW system is to monitor the load and the electrical energy supplied to the tank. This is not only counterintuitive, but is also contrary to recommended and widespread practice of measuring the solar loop production and applying equation 4 and sometimes Equation 2, as was done in the Itron study (3).

From a utility perspective this is sensible. The utility's prime concern is supplying electrical energy to the tank's electric element. Therefore, of primary interest is not what the SHW system does. Rather, it is what the SHW system causes the tank's electric element to do.

When the solar loop is monitored and the measured energy is used to estimate savings, one makes assumptions about how much of that energy is actually applied in reducing the operation of the electric element. There are many stealth losses on the path to applying the solar loop energy to the tank, including the position of the sensors on the solar loop. These losses can vary from system to system.

However, when the load and electric element are measured and equation 3 is applied, those stealthy losses on the generation side of the system—the solar loop—are already incorporated into the tank and its electric element. In other words, this approach inherently accounts for the net benefit of the solar system, including all the associated losses, before a savings estimate is made. Therefore, the savings are closer to the true values than estimating savings from the traditional method of monitoring the solar loop of SHW systems.

Additionally, the results show that the SHW energy savings ratings are sensitive to the size of the hot water load. Larger loads have potential to produce larger savings. At some point, however, an increase in the size of the load will have no further potential for savings because the maximum production capacity of the SHW system will have been reached. This, of course, is intuitive.

7. IMPLICATIONS AND RECOMMENDATIONS

There are a number of implications and recommendations derived from our findings.

First, while our data show with reasonable certainty that the most accurate way of estimating SHW savings is to monitor the load side of the system, we studied only one location—Phoenix. While we don't expect to see radically different results for other geographical areas, some testing should be done to verify this expectation.

Second, based on our findings, we recommend that any SHW monitoring program include measurements of the load side of the system, including the energy in the draws as well as the energy consumed by the electric element in the tank. And we recommend that equation 3 be applied to estimate the savings.

Third, we suggest that further work be done to explain in more detail the bias in the accuracy of the equations as a function of the size of the load. One possible explanation for these trends is that the temperature of the tank is affected by the size of the load, which affects heat losses and these losses affect savings. But additional work is needed to provide a more thorough explanation.

Fourth, it is clear that SHW savings are a function of the size of the load. Therefore, the OG300 ratings are also a function of the size of the load. As Burch and Thornton discuss in some detail, the average hot water loads can and probably do vary among different areas (4). Phoenix is one location where residential hot water loads are suspected of being smaller than the size of the load that SRCC used to determine the OG300 ratings for SHW systems in that area.

However, data on residential hot water loads are scarce and almost all of them are based on work that is quite old, as discussed by Fairey and Parker (5). While some new data are being collected by researchers at the Lawrence Berkeley National Laboratory (LBNL), their burgeoning database contains little information from areas of southern Arizona where thousands of SHW systems are being installed (6). Therefore, there is currently no way to estimate the accuracy of the OG300 ratings for these regions, nor is there any quantitative basis for re-computing these ratings.

Aphoristically speaking, our finding as well as those from others suggest that some OG300 ratings might not be accurate for some areas such as Phoenix, but without some good quality data about residential loads there is no way to estimate the magnitude of the problem or how to correct it.

We urge new efforts to measure residential hot water loads in these regions and to include these measurements in the LBNL database. Further, after sufficient load data are gathered for these areas, we urge SRCC to review the data along with our research findings to determine if the ratings should be re-computed, and to do so if warranted.

8. REFERENCES

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communication concerning the new hot water load database being developed at LBNL.

9. ACKNOWLEDGEMENTS

We gratefully acknowledge the cooperation and assistance of the Solar Rating Certification Corporation in this research. Specifically, we recognize Eileen Pardo, Executive Director, who authorized under non-disclosure agreement the use of SRCC's TRNSYS decks for parts of the analysis. Ms. Pardo also authorized the consulting services of SRCC's modeling experts to assist our team in verifying the correct configuration of the TRNSYS models on our computers.

We also acknowledge the assistance of Steven Long, SRCC's modeling expert, who provided valuable expertise in the preparation of the TRNSYS models and assistance in interpreting the results.

Finally, we extend our appreciation to Jim Huggins, SRCC Technical Director, and Jay Burch of NREL, both of whom provided technical consulting regarding the concepts and approaches in the experimental work involving the load and energy factor analysis.

This work was sponsored in part by the University of New Mexico.