A Realistic Hot Water Draw Specification for Rating Solar Water Heaters

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A REALISTIC HOT WATER DRAW SPECIFICATION FOR RATING SOLAR WATER HEATERS

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ABSTRACT

In the United States, annual performance ratings for solar water heaters are simulated, using TMY weather and specified water draw. Bias stemming from lack of realism in the current ratings draw includes: i) low flow rates boost systems with load-side heat exchangers; ii) low mains temperature boosts performance for all solar water heaters; and iii) an invariant draw profile can't properly credit larger storage volumes vs. smaller and doesn't portray realistic variations south to north. A more-realistic ratings draw is proposed that eliminates most bias by improving mains inlet temperature and by specifying realistic hot water use. This paper outlines the current and the proposed draws and estimates typical ratings changes from draw specification changes for typical systems in four cities. Average change in the ratings from the proposed draw is ~8%.

Keywords: solar water heaters, ratings, draw profile, mains temperature

1. INTRODUCTION

Annual performance ratings for solar water heaters (SWHs) at sites across the United States are issued by the Solar Rating and Certification Corporation (SRCC) under its OG300 Guidelines (1).[1] Ratings users include consumers, incentive organizations, utilities, industry suppliers, and analysts. For some of the user groups, including incentive organizations and utilities with solar water heating programs, calculations made on the basis of the ratings have real monetary consequences; they want performance estimates that are realistic and have no bias by technology or location.

A draw specification gives the use of hot water and the mains inlet temperature over a year. It should be as simple as possible, but no more so. Simpler draws and rating processes reduce cost and provide easier interpretations and explanations, but introduce bias if made too simple. Draw-induced bias can be eliminated by making the rating draw "totally realistic". However, real draw profiles are extremely variegated and complex, and confuse interpretations. Realism must be balanced against simplicity. Bias from the draw specification should be significantly less than desired error in the rating (which is 10% for SRCC (1)).

The current standard test for all water heaters (WH) induces bias for one recently-significant technology, leading to impending changes in the test (2,3). Tankless water heater performance was overestimated by ~10%, basically because the proscribed six draws in the standard test (3) are an order of magnitude too few. New draw profiles being proposed have to represent relevant statistical distributions derived from field data (2), similar to what is done here in proposing this new profile.

In this paper, we first lay out the existing SRCC draw specification, and compare with realistic draws. The current draw induces several biases. Keeping both accuracy and simplicity in mind, we propose a new draw specification to mostly eliminate these biases. It has both fixed-volume and tempered draws. We then compare these two draw patterns in numerical simulations to illustrate the magnitude of the existing biases. Lastly, we point out remaining biases in the proposed specification, stemming from omitting vacations and day-to-day variability to keep the draw simple.

[1] The SRCC "one-day" ratings issued under OG300 are not of concern here; that draw profile is set by the DOE standard test (3).

2. CURRENT SRCC DRAW SPECIFICATION

An annual draw specification gives the *draw profile* (flow rate of hot water ($m_{draw}(t)$) and *mains inlet temperature* ($T_{mains}(t)$) over a year. The current SRCC profile is shown in Fig. 1. The draw is assumed the same every day. There is one draw each hour. Derived by averaging over hourly data, this profile is an *ensemble average,* implying an implicit and spurious "smoothing" of usage, compared to real patterns. Patterns in real houses are more clustered than indicated in Fig.1.

Fig. 2 shows the annual inlet temperature T_{mains} in Helena, MT, from data, the proposed algorithm (4), and the current SRCC algorithm. The SRCC draw is systematically too low by ~5 ^{o}F, and it has seasonal amplitude that is too small by an order of magnitude. The SRCC data is derived from monthly-average outputs in FCHART (5).

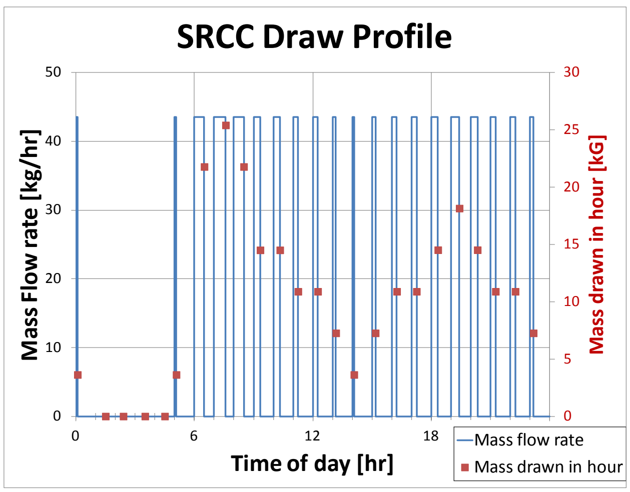

Fig. 1. Flow rate (left axis) and hourly volume (right axis) of the current SRCC profile. The width of the flow rate curve is the duration of that hour's draw, and is proportional to volume.

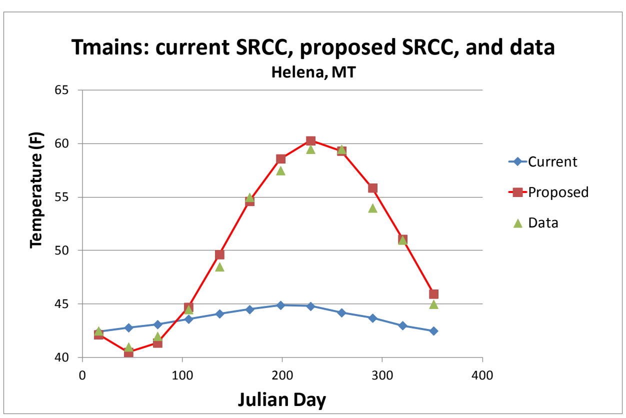

Fig. 2. Mains inlet temperature for Helena, MT: current SRCC (1), proposed, and monthly-average temperature data (4).

3. REALISTIC DRAWS- MORE OR LESS

An extensive study characterizing draws from field data serves as the starting point for this work (6,7). That work was done to provide realistic draw profiles as the basis to properly analyze components whose performance depends significantly on the profile (such as hot water distribution systems and tankless water heaters). A statistical draw generator was created to produce draw profiles at level of seconds, by using Monte-Carlo based on matching empirical distributions (6).

We note that there is an on-going study to statistically characterize draws, using a database with currently ~180 house-years of draw data (2). This repository will provide the distributions that will be the truth standard for proposed new draw patterns for a simulated use test draw.

3.1 Tempered and untempered draws

Refs. (6, 7) postulate two different types of draws: *tempered* and *untempered*. Untempered draws are of fixed-volume (dishwashers and washing machines). For untempered draws, hot water is drawn from the water heating system directly into the machines without any admixture of cold water. Tempered draws include sinks, baths, and showers, where there is direct interaction with human skin. Water is tempered to comfortable use temperatures by mixing cold and hot water to achieve the desired end use temperature (T_{use}). T_{use} is in the range ~105 – 110 ^{o}F, with 105 ^{o}F used in this paper, as in (2).

The fraction of hot water drawn from the hot tank in a tempered draw is:

$$f_{hot} = (T_{use} - T_{mains})/(T_{hot} - T_{mains}), \qquad (1)$$

where T_{use} is the use temperature and T_{hot} is the hot source temperature. The fraction of cold water is $(1 - f_{hot})$. For a fixed T_{use} and T_{hot}, f_{hot} depends on T_{mains}, as in Fig. 3. Over the range shown, f_{hot} increases by ~50% as T_{mains} decreases to 40 ^{o}F.

A key assumption in (6, 7) and also made here is that for a given volume level, ***the use of water is on average the same, independent of location and time of year***. The volumes of untempered and tempered water are assumed to be the same, on average, for all sites and times. An important implication of this assumption is that the hot water drawn from the water heater will vary with the climate and season. Fig. 4 shows the volume of 125 ^{o}F hot water drawn from the auxiliary tank in four cities, given the same volume of tempered water (75.2 gal/day) and same volume of untempered water (13.2 gal/day). Hot water used is ~64.3 gal/day in Knoxville, TN, but varies ~20% at other sites, because $T_{mains,avg}$ differs by ~30 ^{o}F. In

Fig. 4, “no solar” means there is no solar pre-heating system, only the conventional water heater. Similarly, hot water use varies seasonally for the same overall use, with lower hot water use in the summer when T_{mains} is highest, and higher hot water use in winter. Fig. 5 shows the seasonal variation in four cities. In Knoxville, volume varies ± 25% from the average value. All sites show lower volume in summer, reducing summer load compared to the average.

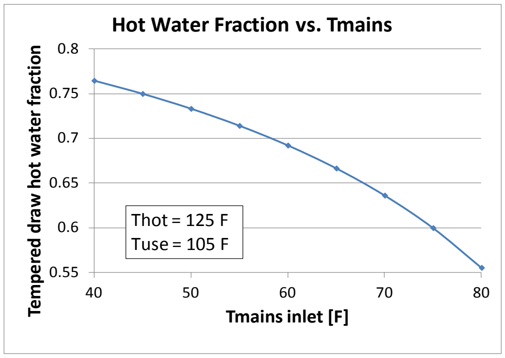

Fig. 3. Fraction of hot water in a tempered draw for fixed T_{hot} and T_{use}, as a function of T_{mains}.

Refs. (6, 7) provide algorithms for the daily volume of tempered and untempered draw as a function of the number of bedrooms in the house. The fraction of each type is independent of the overall draw volume, and will be used to set volumes for the three different SRCC draw volumes.

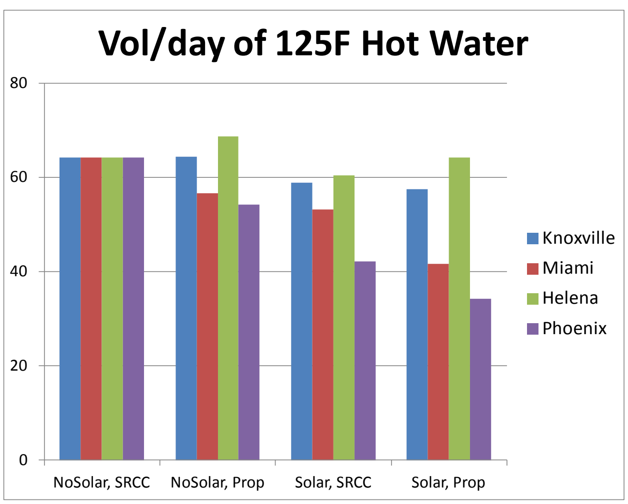

Fig. 4. Variation in four cities of total annual hot water drawn from hot tank, for the same use of tempered + untempered draws. “NoSolar” means the solar pre-heat is not present.

3.2 Draw use: patterned and random

Draw data are complex. Toward simplifying and deriving an appropriate rating draw, we classify draws into *patterned use* and *random use*. Fig. 6 shows six days of water draw at eight different end use points in a two-person household averaging ~ 20 gal/day use (8). Repeated patterns are evident upon scrutiny. Weekdays, there are showers around 6 AM, and kitchen and dishwasher activity in the evenings. There is a typical difference apparent between weekdays and weekends. But not every day has the same patterns, there are unoccupied periods, and there are draws that do not fit any evident pattern. Like Fig. 6, data from other homes typically show mixtures of random and patterned use, with (especially weekday) use clustered around house-hold specific times for daily activities. Most draws by number are sink draws, and most end uses are somewhat clustered together in time, as indicated in Fig. 6.

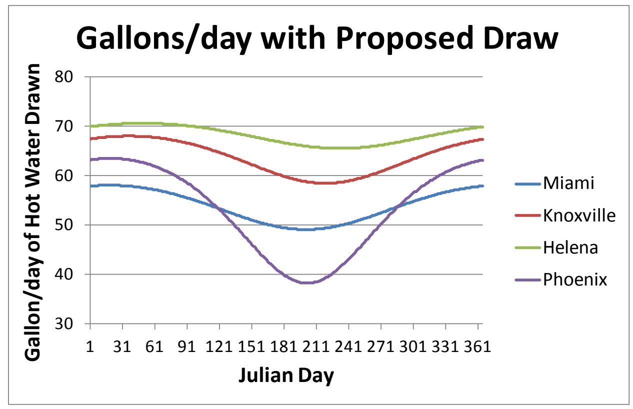

Fig. 5. Daily draw volume as a function of time of year, using the proposed draw (no SWH present).

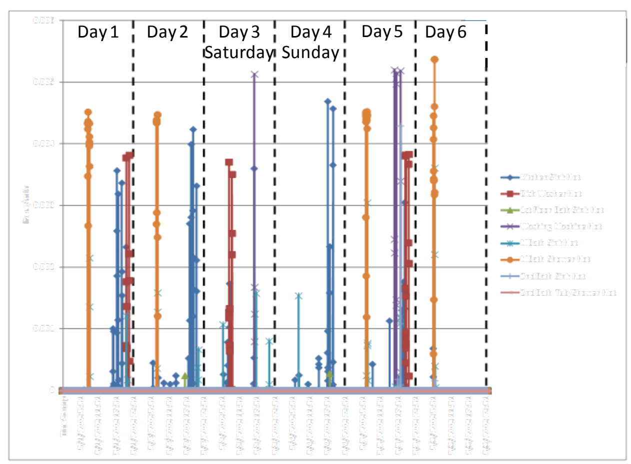

Fig. 6: Water usage from a home with 2 occupants (8). The vertical dashed lines indicate midnight.

3.3 Draw flow rates

The distribution of flow rates weighted by volume from a 12-house study in the Northeast is shown in Fig. 7 (8). There is a wide distribution of flow rates, but most volume use is centered at lower flow rates corresponding to sink, shower, and dishwasher use. Higher flow rates above 2 gpm had a 10% share of volume.

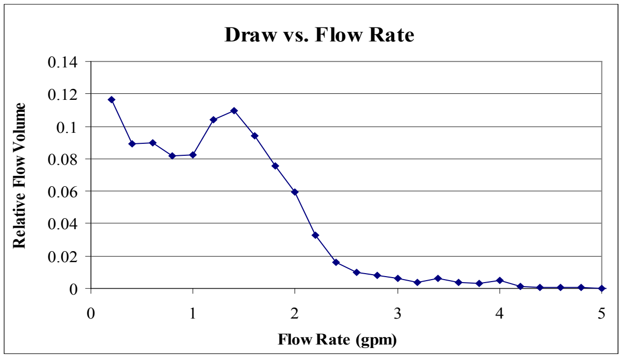

Fig. 7. Fraction of hot water volume in .25 gpm bins, from 0 to 5 gpm (8). Most draw volume is below 2 gpm.

3.4 Mains inlet temperature

Fig. 2 shows mains temperature for Helena, MT, from the current SRCC algorithm and the proposed algorithm (4). The two algorithms have the same overall form:

$$T_{mains,} = T_{amb,avg} + \Delta T_{offset} + R\Delta T_{amb}\sin(\omega_{ann}t - \phi_{mains}), \quad (2)$$

where $\Delta T_{amb} = [(T_{mon,max} - T_{mon,min})/2]$. T_{mains} is linearly related to $T_{amb,avg}$, and the annual fluctuation in T_{mains} is taken as a fraction R of ΔT_{amb}. In the SRCC case, $\Delta T_{offset}=0$, R is taken as a constant at 0.05, and ϕ_{mains} is constant, set to give T_{mains} minimum at $1/8^{th}$ of the solar flux cycle (~Feb. 5 in the north). As proposed here, $+\Delta T_{offset}$ is set to 5 ^oF, and R and ϕ_{mains} are linearly correlated with average annual temperature:

$$R = a_1 + a_2T_{amb,ann}; \text{ and } \phi_{mains} = a_3 + a_4T_{amb,ann} \quad (3)$$

where the coefficients a_i are given in (4). Fig. 2 shows that the data and proposed algorithm agree well in Helena, whereas the current algorithm underestimates temperature by about 5 ^oF on average. It is shown in (4) that the new algorithm fits data very well from eight of nine locations. The exception was Duluth, MN (HDD = 9818 ^oF-day), where decoupling of ambient from ground through significant freeze/thaw and snow cover possibly explaining why temperatures ~10 ^oF below the data were predicted. New data sets will be analyzed in the future.

It is expected that the mains water temperature change, by itself, introduces about 5%-10% variation. For the linear form, collector efficiency varies as in Eqn. 4. A variation in T_{mains} of δT_{mains} induces an increase in the operating parameter $(T_{in} - T_{amb})/I_{inc}$ and reduction in efficiency, as shown in Fig. 8. For constant T_{amb} and I_{inc}, the linear collector efficiency equation implies:

$$\delta\eta_{col}/\eta_{col} = - F_rU_l*\delta T_{mains}/(\eta_{col}I_{inc}) = -\delta Q_{loss}/(Q_{use}) \quad (4)$$

It can be seen that the efficiency variation depends on the slope of the efficiency curve, which is the collector F_rU_l value.

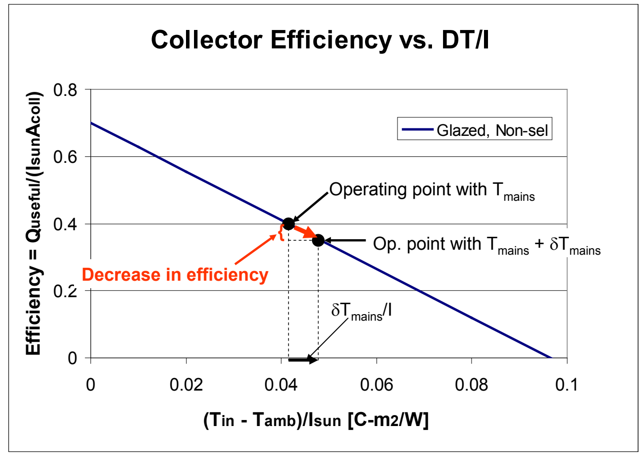

Fig. 8. Collector efficiency plot, graphically indicating the decrease in collector efficiency with $\delta T_{in} \sim \delta T_{mains} > 0$.

4. PROPOSED RATING DRAW

The proposed draw profile is shown in Fig. 10 for the medium draw volume case. The draw specified here implies 64.3 gal/day use of 125 ^oF water in Knoxville when overheating from solar is absent. The draw is shown in Fig. 9 and Table 2. The draw totals 75.2 gal. of tempered draw (hot + cold) and 13.2 gal. of untempered machine draw (hot only). Multiple clustered sink draws and showers are aggregated in single draws, keeping the profile simpler. The volume of hot water in the tempered draws depends on (T_{mains}, T_{use}, T_{set}). For SRCC values T_{use} = 105 F and T_{set} = 125 F, the tempered draw hot water use is 51.1 gal in Knoxville, TN, on average, for total daily draw of 64.3 gal/day in that city.

Fig. 10 shows the distribution in time bins of the proposed draw and the current SRCC draw. It can be seen that the time profiles are reasonably well-matched, and correspond well to ASHRAE profile. Fig. 11 shows the distribution in flow rate bins of the current and proposed draws. The SRCC draw concentrates the flow rates in the low-flow bin entirely. The proposed draw provides a reasonable match to the data.

5. ANTICIPATED RATINGS CHANGES

In order to exemplify the expected changes in the ratings from the proposed draw specification, numerical simulations were done for a typical SWH with the current and the proposed SRCC draw specifications. The collector and system parameters are shown in Table 3.

Savings are calculated as:

$$Q_{saved} = [Q_{aux,ref} - (Q_{aux,sol} + Q_{parasit,sol})] + (Q_{deliv,ref} - Q_{deliv,sol})/\eta_{conv} \quad (4)$$

The last term is a correction for unequal delivery of energy to the load between the solar and the no-solar reference (SRCC defines the reference as either an electric storage tank WH or gas storage tank WH). The correction term is small for the cases here.

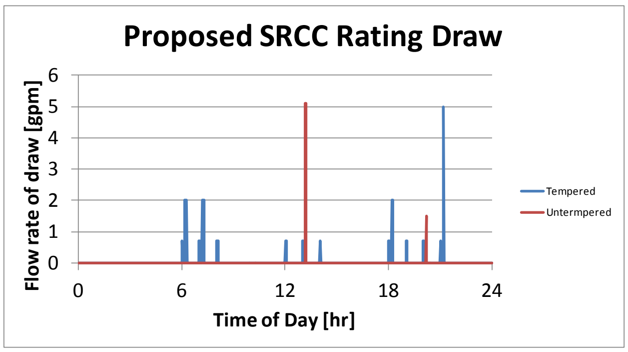

Fig. 9. A proposed daily-invariant draw schedule, which has clustered draws, and both tempered and untempered draws.

TABLE 2. PROPOSED DRAW PROFILE

End use:	Sink	Shower	Bath	DshWasher	ClWasher
Flow (gpm)	0.7	2	5.0	1.5	5.1
Hour of day:	=====Tempered=====			-----Untempered-----	
0					
1					
2	Table gives the volume of each draw in gallons				
3					
4					
5					
6	1.4	16.0			
7	1.4	16.0			
8	5.6				
9					
10					
11	2.8				
12	2.8				10.2
13	2.1				
14					
15					
16					
17	2.8	8.0			
18	3.5				
19	1.4			3.0	
20	1.4		10.0		
21					
22					
23					
Totals:	Tempered: 75.2 gal			Untempered: 13.2 ga	
Hot water:	51.1 gal			13.2 gal	

Fig. 12 shows the variation of savings in four cities due to changes in the draw. Four cases are shown covering changes when both the draw profile and draw temperature change, and when only one of them changes. Also shown is the volume of hot water draw flowing through the solar pre-heat. For the SRCC draw, 64.3 gal/day is delivered to load *after the tempering valve*; but the hot water draw is less than this, because water comes out of the auxiliary tank hotter than the tempering valve setpoint and the tempering valve mixes cold water into the flow to temper to T_{set}. The water comes out above T_{set} because the SWH has recently supplied water significantly hotter than T_{set}. The volume drop in Phoenix, the hottest and sunniest location, is striking in all cases. For the proposed case, the variation in water flow contains both summer over-temperature and tempered water draw effects.

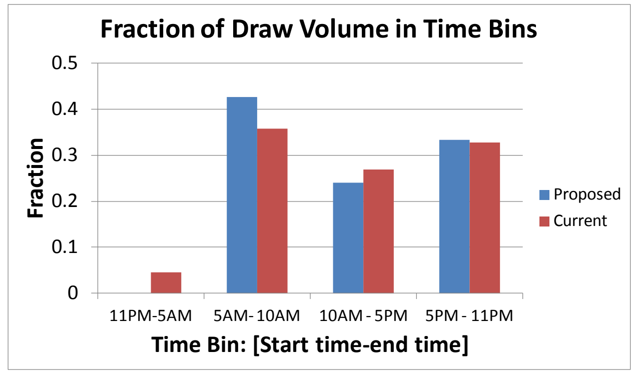

Fig. 10. Fraction of draw volume in 4 time bins, for current and proposed draw profiles.

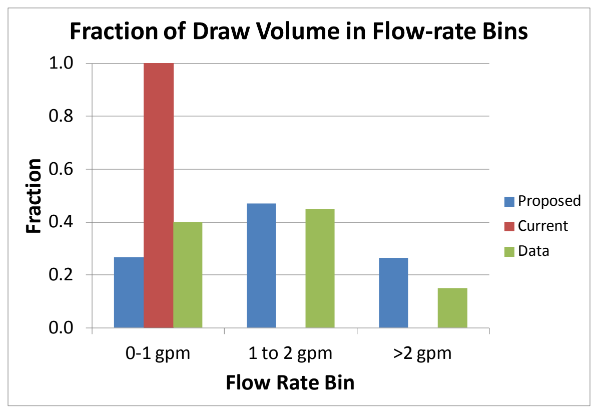

Fig. 11. Fraction of draw volume in 3 flow rate bins, from current SRCC profile, proposed profile, and from data (9).

Fig. 12 shows there is a decrease in the ratings when both the profile and temperature are changed (proposed draw). The average decrease is 12% for the case here. Savings increase slightly in Helena, because the hot water draw is ~14% larger than the current SRCC assumption and savings will always increase with more draw. Conversely, when the water draw is significantly lower than the SRCC case, the savings will decrease significantly also. When keeping the same profile and changing only the temperature (p=S,T=P), the results isolate the effect of temperature alone. It can be seen that there is a reasonably consistent drop in savings, of about 8% or so, consistent with Eqn. 4. When keeping the temperature unchanged and changing the profile (p=P,T=S), the changes show the effect of the changes in volume of hot water draw. Both effects are present when both factors are changed. It is noted that there was no significant change in these conclusions when a non-selective case was simulated.

TABLE 3: SYSTEM PARAMETERS

Collector		
Area	6 m^2	
Orientation	~Latitude tilt[1], due south	
Selective glazed[2]	0.7	3.5
Non-select. Glazed[2]	0.7	7.5
Solar Tank		
Volume	0.3 m^3 (79.3 gal)	
U-value	0.556 W/m^2-°C	
Auxiliary Tank		
Volume	0.15 m^3 (40 gal)	
U-value	0.981 W/m^2-°C	
Piping (hard copper)		
Length (sup. + ret.)	15.24 m (50 ft)	
U-value	2.27 W/m^2-°C	

1) Tilt is at the optimal tilt, which is “near” latitude tilt, as in (cc)
2) The two cells to right give $F_r \tau\alpha_n$ and then $F_r U_l$ [W/m2-K]

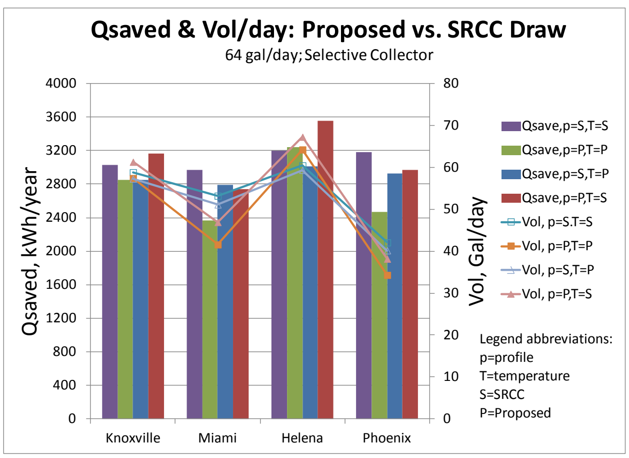

Fig. 12. Q_{saved} and $V_{draw,day}$ for four cities and four possible combinations of draw specs.

The low flow rates in the current SRCC draw bias high the savings from systems with a load-side heat exchanger. This bias is primarily because the heat exchanger effectiveness is spuriously near 1.0 at very low flow rates, giving an advantage vs. realistic flow rates where the effectiveness is typically 0.6 - 0.9. Simulations were done with the same system as above, except the draw is through a load-side heat exchanger of 75’ of 3/4” bare copper tubing in the solar tank. It can be seen in Fig. 13 that the decrease in savings is ~17%. Also notice that the draw volume variation in this case is much smaller, indicating not as much summer overheating. Lastly, it is noted that we do not know if there is bias from the proposed profile, but as its flow rate distribution is realistic (see Fig. 11), we can assume it is more realistic with less bias than using the current distribution.

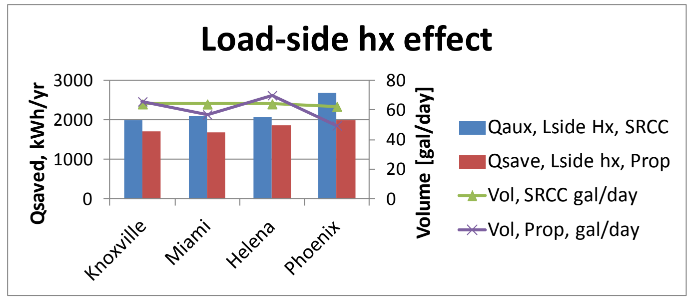

Fig. 13. Change in auxiliary usage and daily hot water draw volume for SRCC vs. the proposed draw, for a system with a load-side heat exchanger.

The current SRCC profile overestimates the summer water heating load, both by generally overestimating volume and always overestimating the temperature difference. This has little effect on small systems, where saturation rarely occurs, except for very hot and sunny climates. Fig. 14 shows that at 3m^2 size, there is little change to the savings except for Phoenix. This is partly because there is little overheating under either draw profile, except for Phoenix. In Phoenix, the SRCC profile minimizes overheating; this leads to anomalously-better performance vs. the proposed, realistic draw, which overheats considerably more. Fig. 15 also indicates that at the large 9m^2 area, there is significant decrease in savings in all cities when changing to the proposed draw. In Helena, the increase in draw volume overcomes the decrease from summer overheating (which is less in Helena).

System sizing is affected by the draw specification. A common method to size systems to avoid routine overheating is to just meet 100% of the load on a clear, hot summer day. With summer load decreased significantly in the proposed draw, systems sized with the proposed draw will be smaller than those sized using the current SRCC draw by the ratio of the peak loads on the peak day, i.e., size of the system is reduced by the ratio $Q_{load,prop\text{-}draw}/Q_{load,SRCC\text{-}draw}$. The ratio can be over 50%. Overheat protection is going to become even more important an issue with the new draw.

6. BIAS FROM LACK OF VARIABILITY

The proposed draw has no variability in the daily draw pattern. Variability includes vacations, weekday/weekend differences, and random day-to-day draw volume variations. We have chosen to not incorporate variability, choosing an invariant draw for rating, to keep the description and interpretation of data as simple as possible. However, that choice biases savings high.

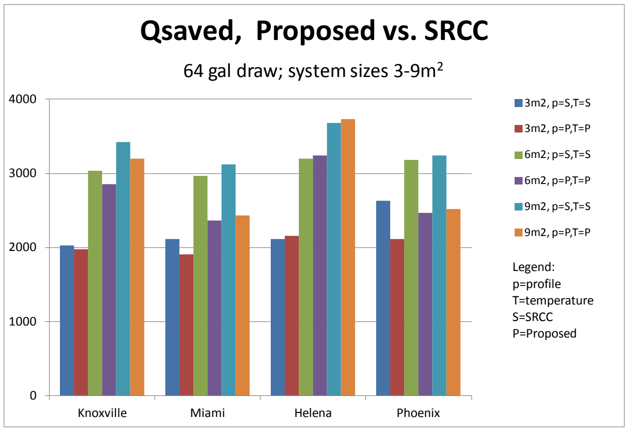

Fig. 14. Q_{saved} for 3 system sizes in 4 climates for the 64 gal case, with the current SRCC and the proposed draw.

Vacations. In (6,7), the adopted profiles have 14 vacation days in four segments, during which there is no draw at all and the system stagnates. There are no savings during these days. Assuming vacations are distributed equally in time, we can estimate that the fractional increase in savings from neglecting vacations is

$$\Delta Q_{saved}/Q_{saved}=N_{days\text{-}vacat}/N_{year}=14/365= \sim 4\% \qquad (5)$$

Day-to-day variability. Fig. 15 shows a "normalized" distribution of daily draw volume for 12 homes in the Northeast (9). For each home, the daily-volume distribution for weekdays and weekend days was normalized to the ensemble average weekday and weekend draw volume, to take out the effect of different draw volumes and illuminate only variability. The distributions were then co-added, improving statistics. In this study, the weekends showed a significantly higher volume use (80 gal/day vs. 55 gal/day). The impact of variability depends on location and system size. Using Fig. 15 data, simulations incorporating variability were done. The change of savings for a variable vs. an invariant profile averaged ~8%. Incentive organizations and analysts want realistic ratings, representing the reality in the field, and will likely want to include variability. OG300 suppliers will not want to decrease the ratings, in part because incentives are mostly performance-based and use the SRCC ratings. We feel that further policy discussion is needed.

Variability should be taken into account when designing systems. It has a significant effect on the optimal sizing of the solar storage. Our omission of variability in the proposed rating draw implies that the real boost in savings from larger storages will not be correctly represented. Large-storage systems are thus unfairly treated under both the SRCC and the proposed draw. When the load is constant every day, the storage has to carry only one day of draw. However, when the load is variable day-to-day, the storage must be larger to optimally store energy over multi-day periods. It was estimated in (11) that the storage needs to be about 30% larger to optimally deal with variability, compared to a tank optimized for an invariant pattern with the same daily average hot water draw.

7. CONCLUSIONS

The current SRCC draw induces biases because: i) the chosen flow rate of 0.2 gpm is unrealistically low, and spuriously boosts systems with load-side heat exchangers (+ ~15%); ii) the chosen mains temperature is too low, which boosts performance for all SWHs (+ ~8%); and iii) the invariant draw volume favors larger systems vs. smaller, and favors southern sites vs. northern. A proposed draw profile eliminates most of these biases, increasing confidence in the accuracy of the ratings.

Variability in use of water was not incorporated, to maintain ratings simplicity and make interpretation of hourly data easier. Without variability, performance of current system is overpredicted by about 8%, and larger-storage systems are not properly credited. Further discussion is warranted.

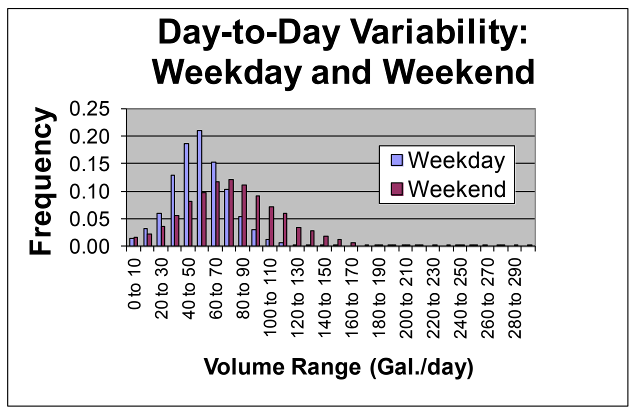

Fig. 15. Frequency distributions of the daily draw volume, for weekdays and weekends.

8. ACKNOWLEDGMENTS

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9. NOMENCLATURE

Symbols:

a_i = temperature correlation coefficients, i=1,4

c_p = specific heat
f = fraction
F_r = heat removal factor
I = solar incidence (power/area)
m = mass flow rate
M = mass
N = number
Q = energy
T = Temperature
U_l = Collector loss coefficient
η = efficiency (collector or system or auxiliary)
δ = variation or change
Δ = difference
$(\tau\alpha)_n$ = collector transmission*absorption normal incidence

Subscripts
amb = ambient condition
aux = auxiliary backup
avg = average
ann = annual, or annual average
col = collector
conv = conversion of fuel to heat in tank
deliv = delivered to the load
draw = draw
hot = hot
inc = incident solar on collector
loss = lost from the collector
mains = water mains inlet
max = maximum
min = minimum
mon = monthly interval
n = normal
par = parasitic energy (e.g., pump, controller)
ref = reference, typically gas or electric water heater
sav = energy saved by the solar system
set = set point of auxiliary water heater
sol = solar system
use = useful energy from collector, or use of hot water
vacat = vacation
year = year

Acronyms
ASHRAE = American Society of Heating, Refrigeration and Air Conditioning Engineers
BTP = Buildings Technology Program
DOE = U.S. Department of Energy
OG300 = OG300, SRCC operating guidelines for system
SRCC = Solar Rating and Certification Corporation
SWH = solar water heater
TMY = typical meteorological year
WH = water heater

10. REFERENCES

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