CHAPTER

THREE

METHODOLOGY: DRAW REPRESENTATION

The magnitude and timing of residential hot water draws are needed to evaluate the impact of many DHW systems on a utility. Estimates of utility customer hot water usage can be obtained by monitoring the DHW equipment, conducting customer usage surveys, or both. Customer surveys are dependent on market research problems such as self-reporting and statistical analyses. Low level monitoring (utility billing analysis, end-use metering, or Btu metering) requires long monitoring periods and large sample sizes due to high standard deviations. While detailed monitoring (continuous data logging of many variables) can reduce the needed sample size and the duration of the testing period, per site costs are significantly higher than low level monitoring (Christensen, 1994). Thus, metering of large numbers of households is prohibitively expensive, time consuming and dependent on the accuracy of monitoring equipment. Both surveys and monitoring programs are sensitive to sample size. Research has shown that the number of samples needed to characterize a diversified load is higher than most available monitoring (Section 3.2.2). In fact, the only agreement in the literature about residential water draws is that they vary!

To circumvent these problems, a water simulation program, WATSIM, based on metered data and survey results, but with extended demographics and probabilities, was employed. Two other methods of diversified draw representation were also examined, as discussed in Section 3.2.

3.1 WATSIM

WATSIM was developed by the Electric Power Research Institute (EPRI) and contains algorithms based on metering experiments, previous research, and statistics (Hiller et al., 1994). WATSIM made use of an EPRI developmental study that utilized sixteen predictive equations with up to nine independent variables. The equations were used to estimate either weekday or weekend-day hourly average hot water consumption within eight daily time periods (EPRI, 1985). This study estimated that in general, the predictive equations explained nearly seventy-one percent of the actual variation in average hot water consumption during weekday periods, while the weekend-day models explain about sixty-nine percent of that variation (EPRI, 1985).

WATSIM is the best source of hot water load information available today. WATSIM has two main purposes: to simulate various water heater performances, and to create water draw profiles (EPRI, 1992). While WATSIM can model electrical resistance, fossil fuel fired, and heat pump driven residential hot water heaters, it does not model solar water heating systems. To estimate the diversified electrical demand of a large number of electric and solar DHW systems, a large number of individual profiles must be input into TRNSYS (which can model both solar and electric DHW systems). WATSIM is used to create the input water draws for the TRNSYS DHW system analyses. The water draw algorithm has four primary capabilities (EPRI, 1992):

- Creating sets of standardized residential draws.
- Creating sets of "representative" draws given customer characteristics using an automatic water draw generating code.
- Creating sets of "representative" draws for up to 300 households given customer demographics using an automatic water draw generating code. (Nine hundred water draw profiles are possible with some manipulation outside of the main program)
- Concatenating WATSIM and custom residential or commercial water draws files.

The types of input that may be manipulated for each household are events and family characteristics. The full listing of possible hot water events (variations of Table 3.1.1) is found in the Appendix.

Hot water events are set to occur according to the number and characteristics of the persons of household listed in the Demographics Table 3.1.2. Annual simulations (for one family) also contain "statistics" for vacations, weekends, laundry days, and out of town guests. The day of the week for water draws is also a user input. The most distinct differences in WATSIM daily average water draw profiles are between weekdays and weekends. When the automatic generating code is run, it produces two sets of draws: an ASCII file containing an aggregated profile that averages all draws on a five minute basis, and a binary file containing the individual human and machine draws for each profile.

Table 3.1.1: WATSIM Hot Water Events Table

Event Hot Water Characteristics							
Event	**Line #.**	**Event #**	**GPM**	**ON(s)**	**OFF(s)**	**fixed_Q**	**POU Temp.**
profligate shower	0	0	7.0	500	0	0	1
average shower	2	1	6.0	250	0	0	1
conserving shower	4	2	2.0	180	0	0	1
bath	6	3	7.0	300	0	0	1
wash-up	7	4	2.0	100	0	0	1
hands/face	9	5	2.0	30	0	0	1
* small c.w./WC	11	6	1.5	240	0	0	0
small c.w./HC	12	7	3	240	0	0	0
small c.w./WW	13	8	1.5	240	600	0	0
small c.w./HW	15	9	3	240	600	0	0
large c.w./WC	17	10	1.5	390	0	0	0
large c.w./HC	18	11	3	390	0	0	0
large c.w./WW	19	12	1.5	390	900	0	0
large c .w./HW	21	13	3	390	900	0	0
weekday breakfast	23	14	2	20	15	0	1
weekend breakfast	31	15	2	20	15	0	1
lunch preparation	43	16	2	20	15	0	1
dinner preparation	51	17	2	20	15	0	1
lunch dishwash	68	18	2	45	30	0	1
dinner dishwash	78	19	2	45	30	0	1
machine dishwash	91	20	6	60	600	0	0
cleaning	95	21	2	30	120	0	0

* "c.w." represents clothes washing and C, W, and H represent cold, warm, and hot respectively for the wash and rinse cycles.

Table 3.1.2: Demographics Probability Table Example

	Level	Percent	Title
Number of Adults	1	0	NA
2	70	NA	NA
3	0	NA	NA
4	0	NA	NA
Working Adults	0	30	no
	1	70	yes
Number of Children	0	50	NA
One Adult	1	30	NA
	2	15	NA
	3	5	NA
	4	0	NA
	5	0	NA
	6	0	NA
	7	0	NA
Number of Children	0	24	NA
Two Adults	1	24	NA
	2	29	NA
	3	13	NA
	4	6	NA
	5	4	NA
Number of Bathrooms 2 or less in Family	1	80	NA
	2	20	NA
Number of Bathrooms 3 or more in Family	1	17	NA
	2	83	NA
Number of Laundry	0	10	NA
Machines	1	90	NA
Number of Dish Washers	0	30	NA
	1	70	NA
Energy Ethic	0	20	conserving
	1	60	neutral
	2	20	profligate
Lifestyle	0	100	average
	1	0	outdoor
	2	0	church
	3	0	couch potato
Worker Shift	0	80	day
	1	10	evening
	2	10	night

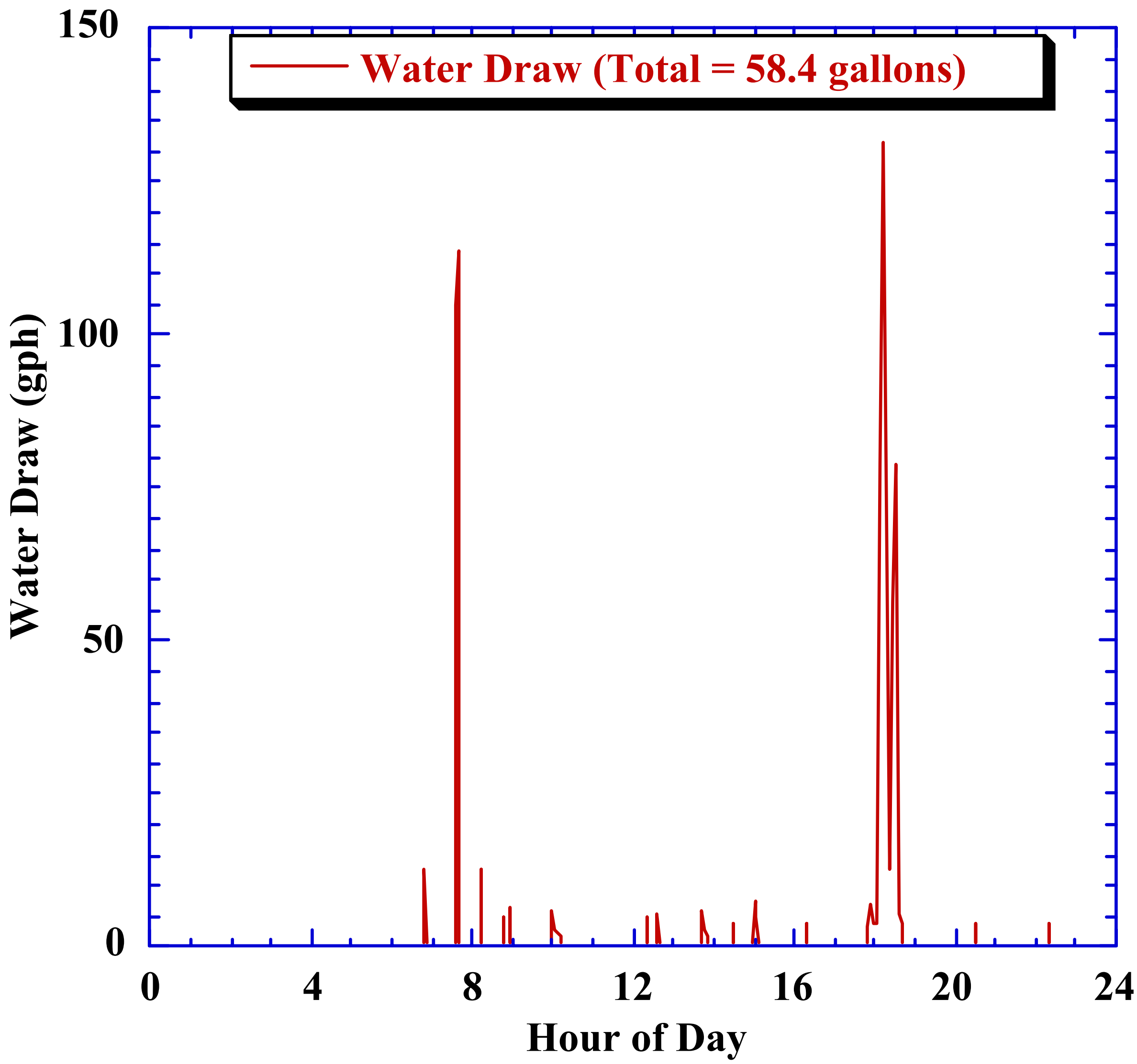

Figure 3.1.1: WATSIM Family of Four - Typical Wednesday

A "typical" water draw for a family of four on a Tuesday is shown in Figure 3.1.1. The largest hot water draws (of the five minute duration) occur at approximately 7:30 a.m. and 6:30 p.m. due to morning showers and evening dish washing, respectively. While the user could follow one family through an entire year, the diversified water generating code provides an analysis of multiple families' hot water usage during one specific day. The average effect of numerous households can be seen in Figure 3.1.2 for ten and three hundred different customers. The instantaneous hot water demand of the average household decreases with increasing sample size, because all residential water draws are not coincident.

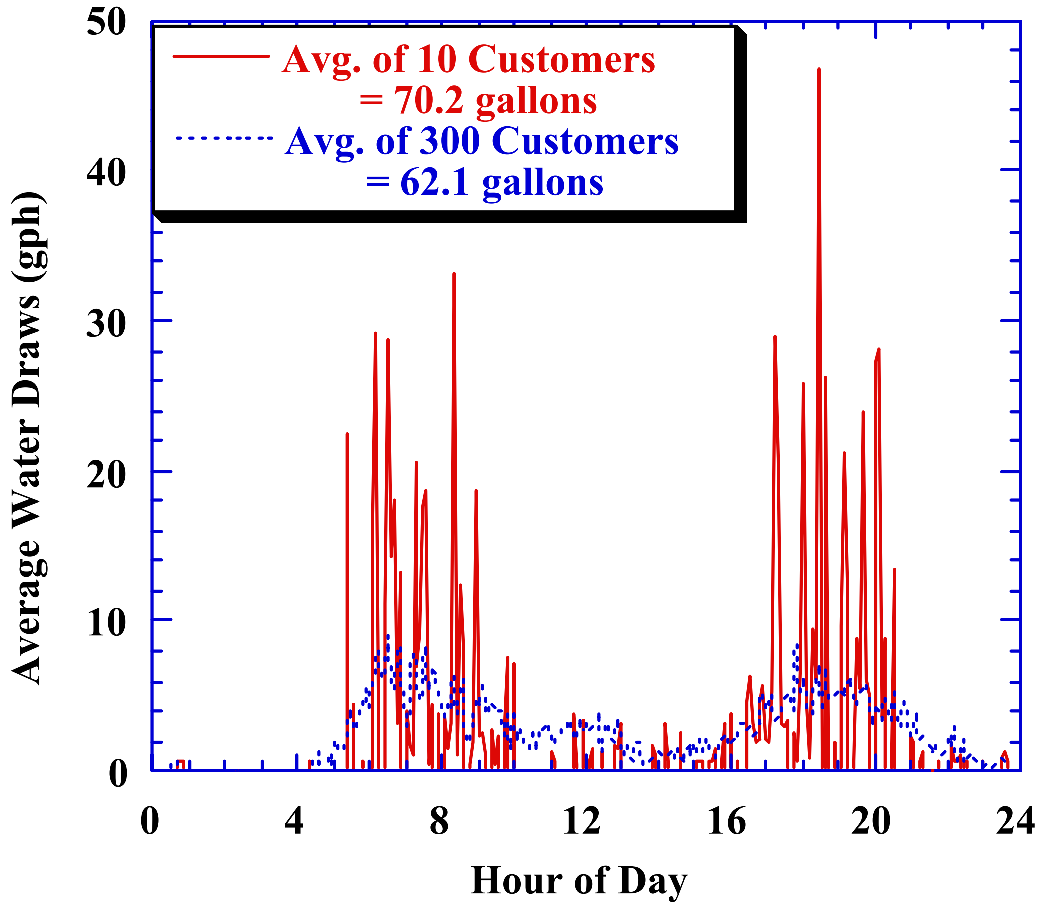

Figure 3.1.2: WATSIM Tuesday Water Draws: 10 and 300 Averaged

Up to three hundred sets of "different" household profiles may be created with WATSIM, while up to nine hundred sets of "different" customer profiles are achievable with some manipulation outside of the main program. To create multiple hot water draw profiles outside of the program, three user-specified inputs are required: day of week, number of households, and a random seed (to start a random number generator). Unfortunately, inconsistencies within WATSIM cast doubts upon the actual randomness (diversity) that it creates. A large enough sample size should produce a relatively smooth average profile. In Figure 3.1.2, even the average of three hundred customer households shows some “spikiness”. Is a sample size of three hundred just too small? To test this, the average of nine hundred households for five different days of the week and the same random seed are shown in Figure 3.1.3.

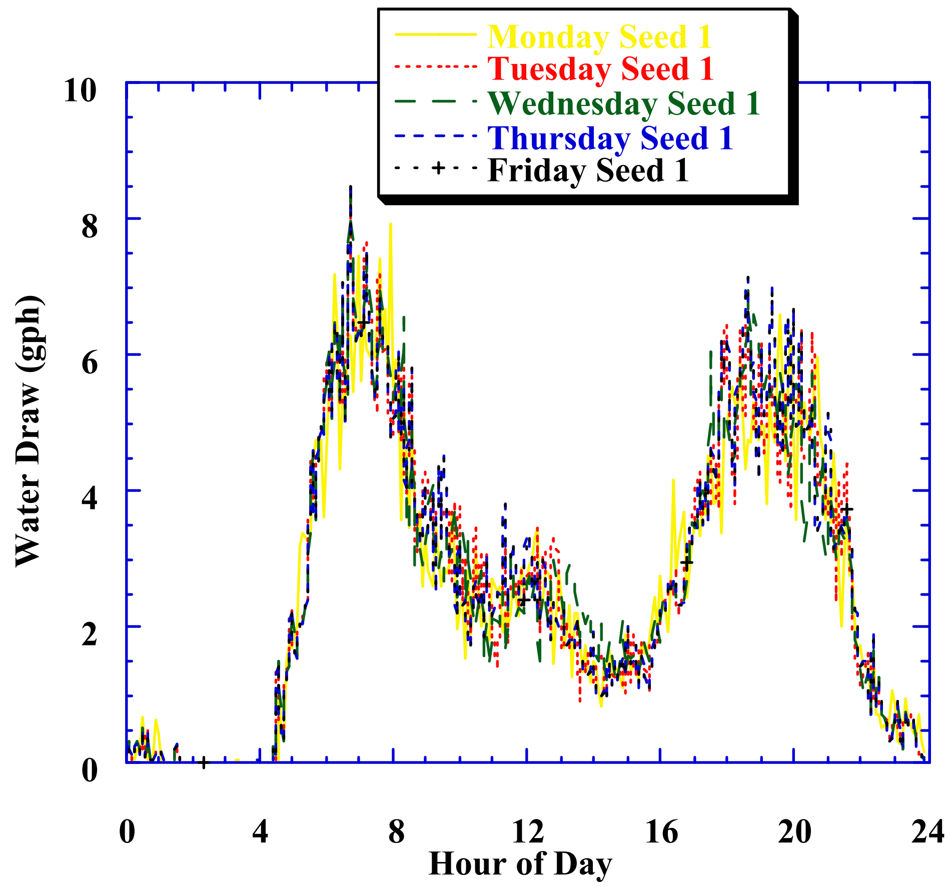

Figure 3.1.3: WATSIM Weekday Draws: Average of 900 Customers Using Random Seed 1

The “spikiness” has obviously not been resolved, even with a tripled sample size (900 households, five weekdays). Those spikes indicate that a large number of households were using hot water during the same five minute time period, which is highly improbable. One explanation for this problem could be that the different days of the week have some set time scheduling consistencies. To test the effect of the random number generator (independent of the day of week), the average hot water draws for 900 households were created for the same day using 10 different random seeds as shown in Figure 3.1.4. These ten averages of 900 were then averaged. The resulting thick line is thus the average of 9000 "different" residential customer water draws. Again, the variance is greater than expected.

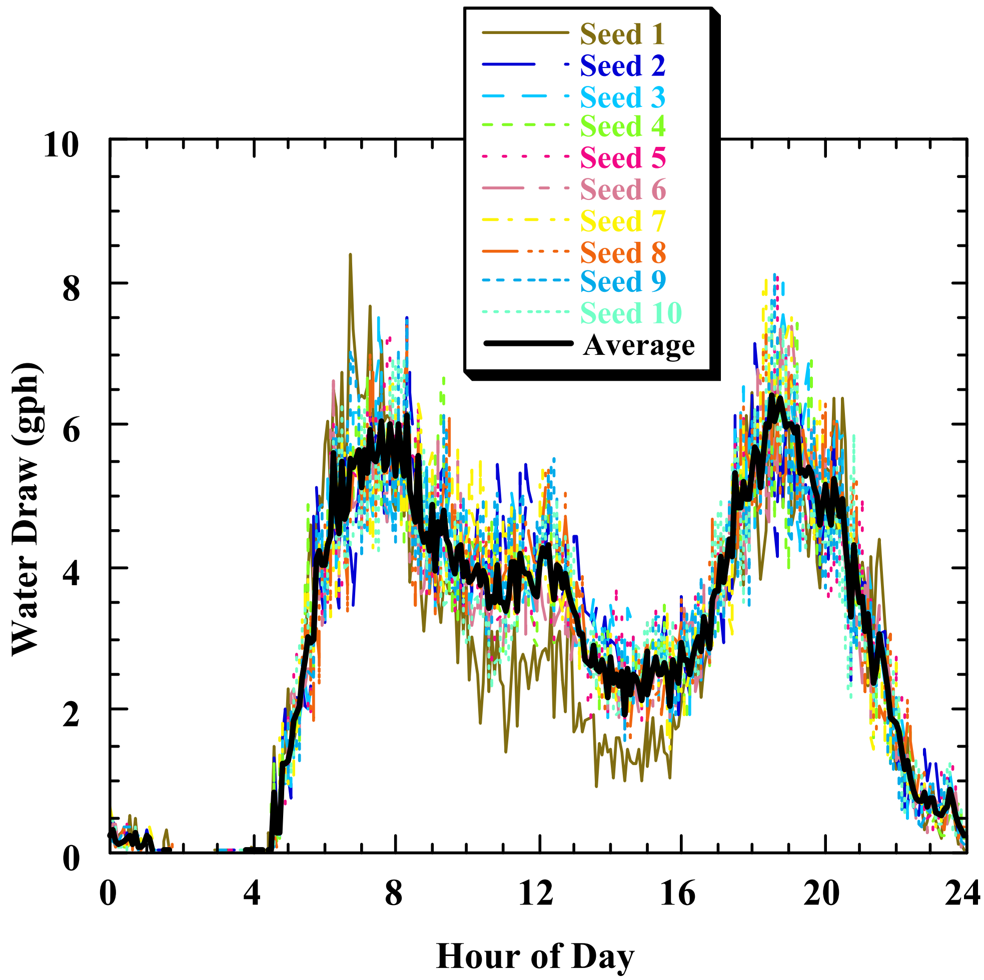

Figure 3.1.4: WATSIM Tuesday Draws: Average of 900 Customers Using 10 Random Seeds

A large number of WATSIM hot water draws are not truly independent, yet research has shown that the sampling size for diversified demand requires between one hundred and one thousand independent customer profiles for acceptable statistical accuracy (Section 3.2.2). If the individual hot water draw profiles from WATSIM were used in TRNSYS to model the diversified electrical demands of different DHW systems, the statistical problems would carry over into the electric utility impact analysis. Since the time of day and magnitude of the electrical demand are critical to the utility impact analysis, individual WATSIM hot water draw profiles cannot be used.

3.2 Statistical Approaches: Diversified Draw Representation

To deal with the statistical problems with WATSIM, without discounting the crux of the data that WATSIM produces, alternative approaches were explored.

3.2.1 Standard Deviations: Random Load Generator

While problems exist, the WATSIM program provides a base for creating a load "diversifier" in TRNSYS. Using average weekday and average weekend loads as a basis, deviations from those loads can be truly randomized to create a more accurate "diversified" load as seen in Figure 3.2.1. This approach is essentially that taken by Grater (1992). He used average hot water loads modified slightly to produce a large number of different average loads. His approach does not yield accurate electrical demand reduction with an on/off heater analysis (Section 3.2.2). Examples of this method are shown in Figure 3.2.1, but due to redundancy this method was rejected.

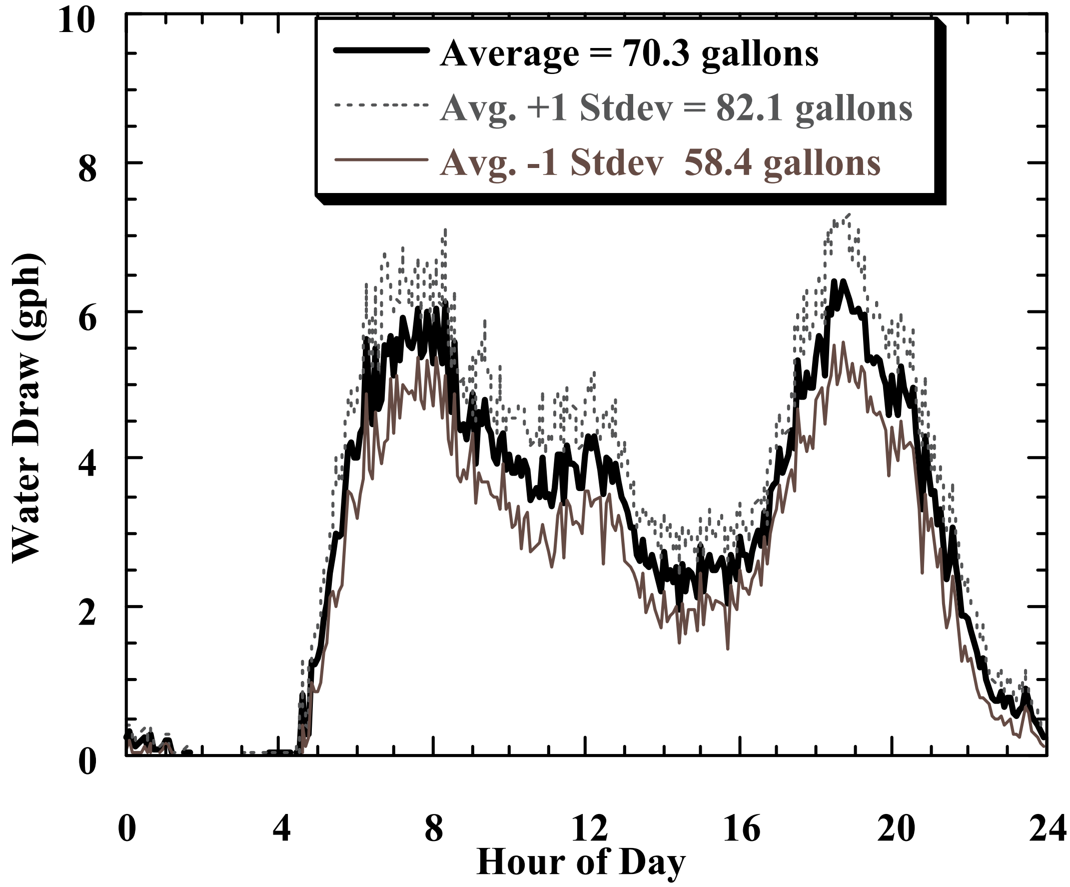

Figure 3.2.1: WATSIM Tuesday Draws: Standard Deviations of the Average of 900 Customers Using 10 Different Seeds

3.2.2 Diversified Demand Sample Size

Keeping the lessons of previous researchers in mind, a large sample size of individual hot water draw profiles and thereby electrical demand profiles are necessary to achieve a diversified electrical demand with temperature level controlled simulations. WATSIM can estimate the diversified electrical demand of up to three hundred customers on a five minute basis. Electric demand cannot be calculated for more than three hundred customers since water draws for more than three hundred households can only be created outside of the main program. Yet, the peak electrical demand at any time becomes increasingly more certain with increased sample size. In addition, the electrical demand follows the water draw directly, with a slight time lag, as depicted in Figure 3.2.2. Since hot weekday afternoons are when summer peaking utilities see their highest system electricity demand, the coincident afternoon peak of the electric and solar DHW systems is of concern. Morning and afternoon peaks occur at 8 a.m. and 7 p.m. respectively in Figure 3.2.2.

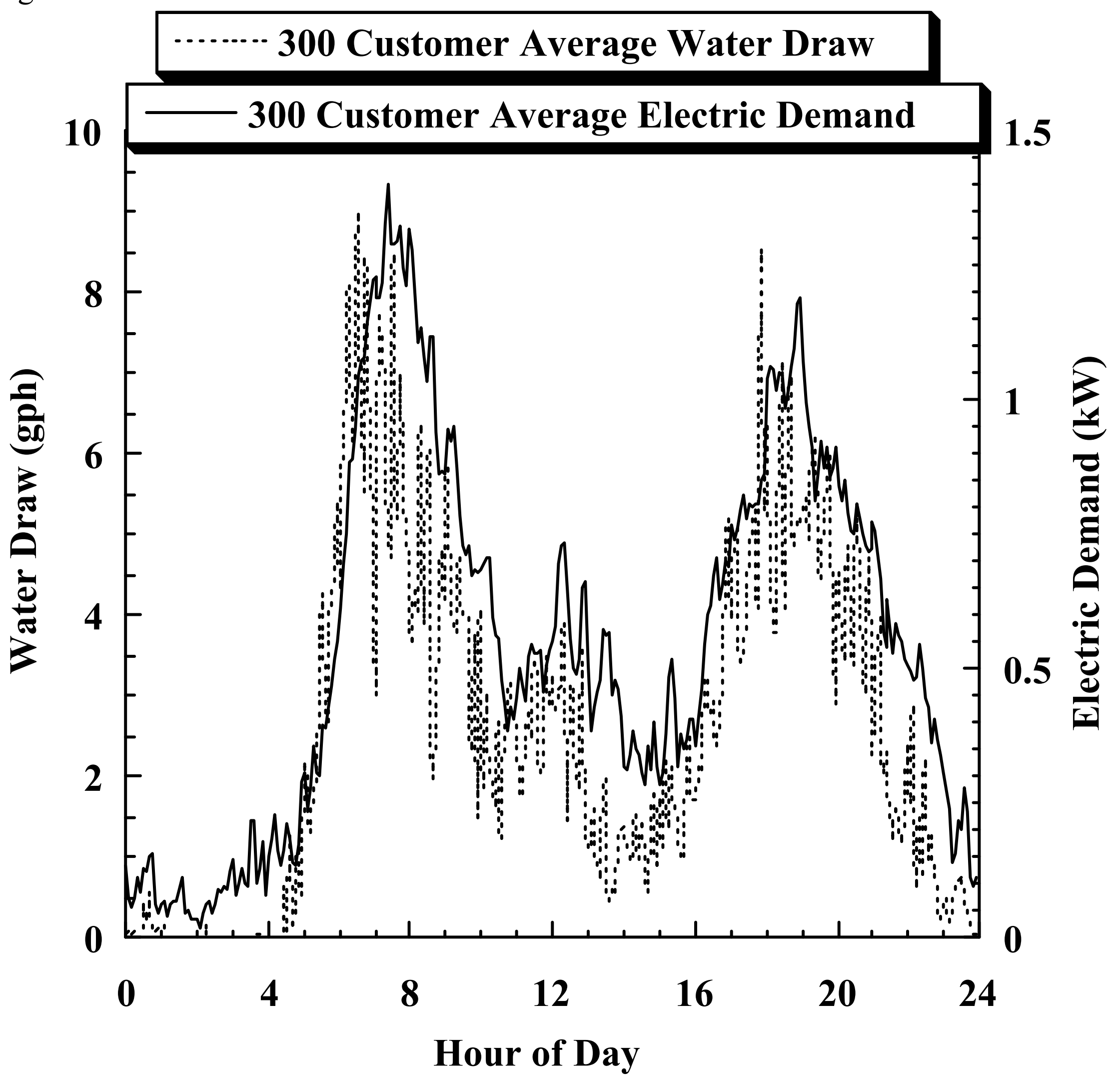

Figure 3.2.2: WATSIM Average Electric Demand (50 gallon tank) and Average Hot Water Draw Averaged for 300 Customers (Tuesday)

The goal of the following approach is to circumvent the water draws completely and base the diversified electrical demand on WATSIM results for electrical DHW systems. The electric DHW system demands could then be extended with a statistical analysis to predict solar DHW system electrical demand. Knowing that the peak electrical demand of one 4.5 kW electric DHW system is 4.5 kW, the “law of large numbers” could be extended to the WATSIM results. In Figure 3.2.3, the peak afternoon and morning demands are graphed on a semi-log scale to see if there is a minimum number of customers at which the peak demand would level off. At such a point, any additional customers added to the group would not cause a significant decrease in average demand. When the peak demands of one thousand customers are averaged, the peak demand (seen by the utility) seems to level off at about one kilowatt.

Figure 3.2.3 shows one limiting SDHW system case: a zero percent solar fraction system that has the same demand as the electric DHW system. The lower bound is a one hundred percent solar fraction system that would yield zero afternoon demand at all times. The morning and afternoon peak demands are important from an electric utility demand reduction perspective. The "law of large numbers" method for determining the peak electric demand seemed reasonable until the SDHW system impact analysis was extended to an annual basis, in which 8760 hours are considered. The analysis shown in Figure 3.2.3 was performed for each hour of one day, but results were less accurate because each hour demand was more uncertain than the peak demand for a larger period; i.e., morning or afternoon. The hourly analysis was also much more time-intensive.

While the curve shown in Figure 3.2.3 could be made for each hour of one day, the annual affect of different models of solar DHW systems is lost. Thus, hourly analysis of solar DHW system performance on the peak day (when the utility experienced the highest demand) became less important than annual SDHW system impacts on utility, due to emission and contribution to capacity considerations.

Therefore, as the breadth of the thesis research expanded to capacity contribution, the "law of large numbers" method's attractiveness faded.

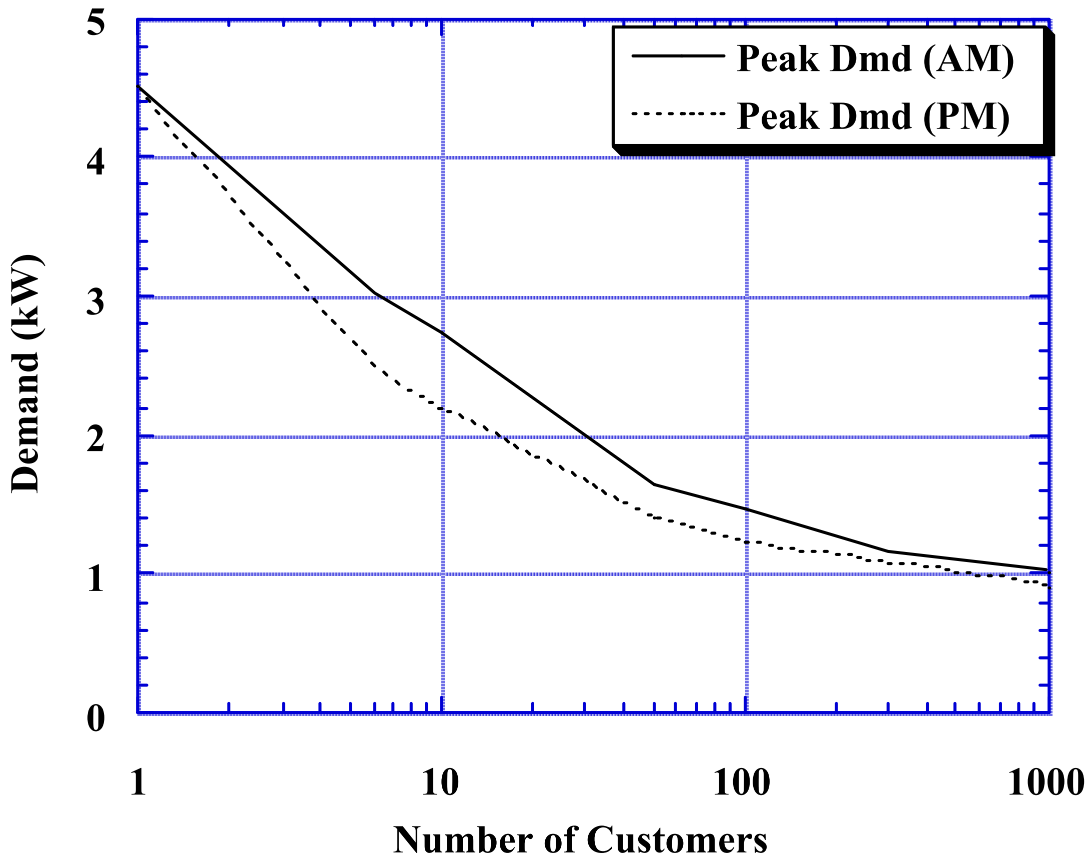

Figure 3.2.3: Peak Demand vs. Number of Households
4.5 kW Electric DHW On/Off Heater (0% Solar)

3.3 Average Draw Representation

Average weekday and weekend-day loads can be derived from WATSIM that agree with other accepted metered and utility produced average hot water loads. The nine hundred "spiky" averages for ten different random seeds, (for five different weekdays and two different weekend-days) were "smoothed" with a graphics program to yield the weekday and weekend-day average hot water draws (in ten minute intervals) in Figure 3.3.1.

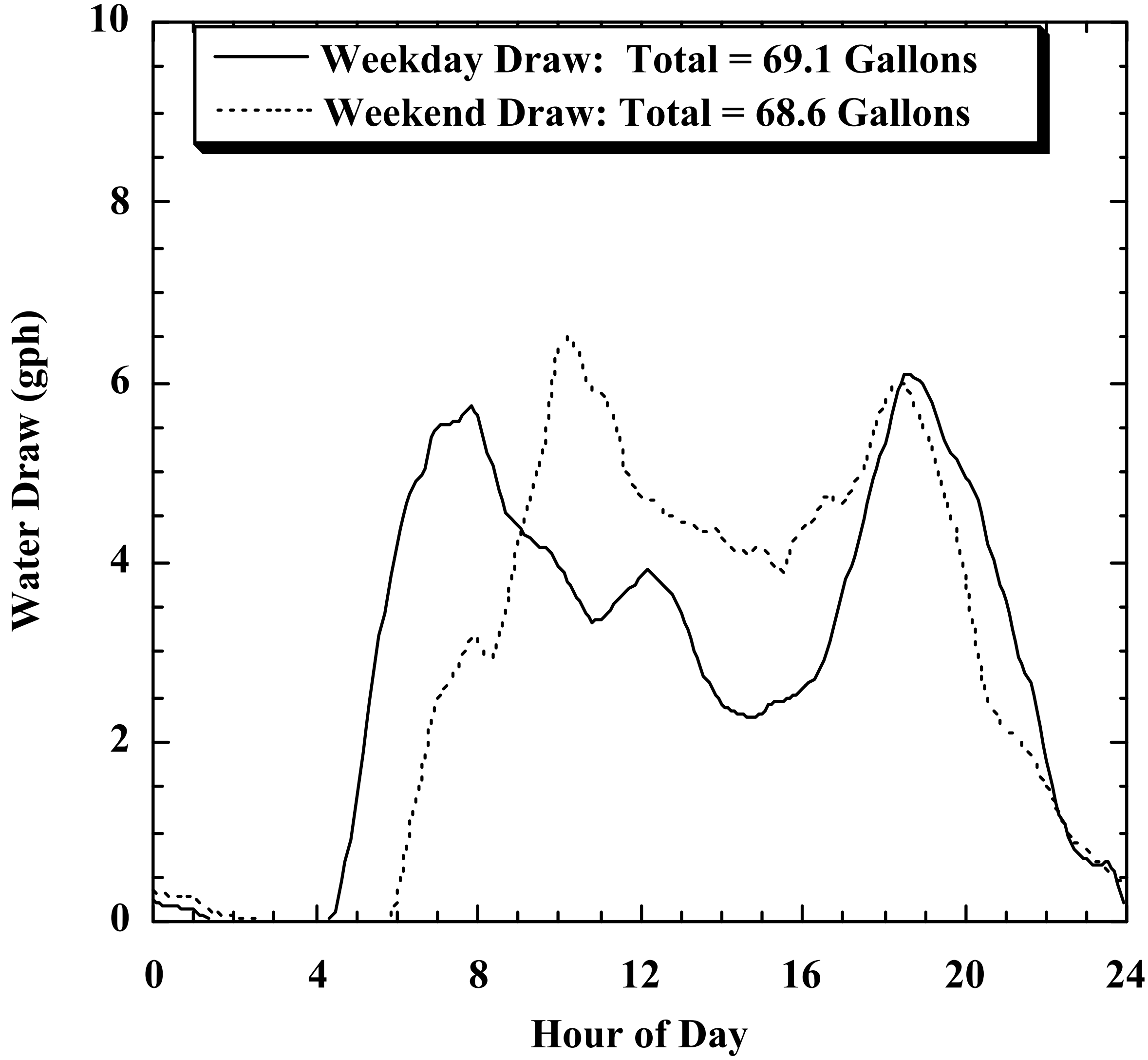

Figure 3.3.1: WATSIM Derived Average Residential Water Draw Profiles

Grater used weekday and weekend water draw profiles adapted from a Wisconsin Center for Demand Side Research database (Grater, 1992). These two daily profiles are compared in Figure 3.3.2. These profiles have a somewhat higher average daily usage than the WATSIM profiles. The Wisconsin weekday draw peaks slightly earlier (between 6 and 7a.m.) than the WATSIM profile, which peaks at about 7:30 a.m. The Wisconsin weekend profile shows a relatively constant average water draw of 5.5 gallons per hour during the day, while the WATSIM weekend profile changes more dramatically, with one peak in the mid-morning and a second that coincides with the weekday profile peak at 6:30 p.m. WATSIM profiles do have the added detail of five minute averages, while the other average water profiles in this section are all based on hourly information.

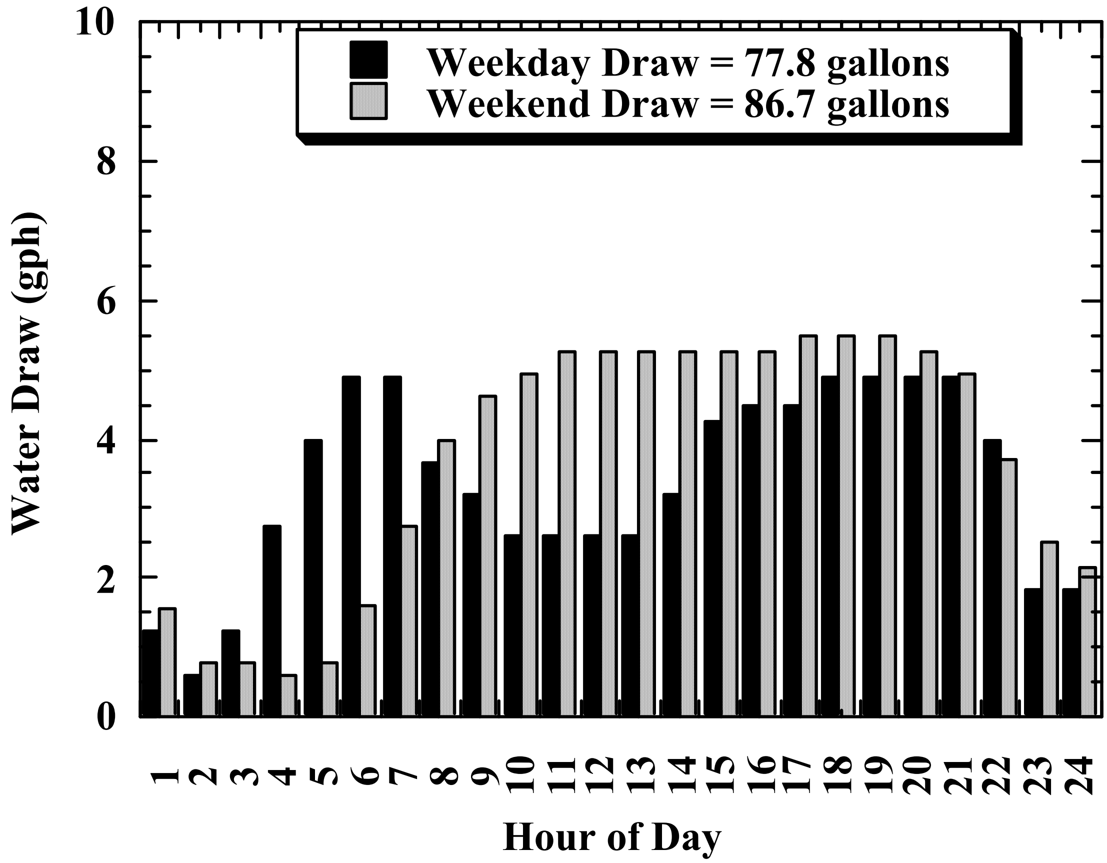

Figure 3.3.2 WI Weekday and Weekend Average Hourly Hot Water Use (Grater, 1992)

An ASHRAE paper reported a detailed analysis of residential hot water usage research (Pontikakis, 1994). Pontikakis listed four separate sources, with varying sample sizes, that estimated the average residential hot water load profile. All four are shown in Figure 3.3.3.

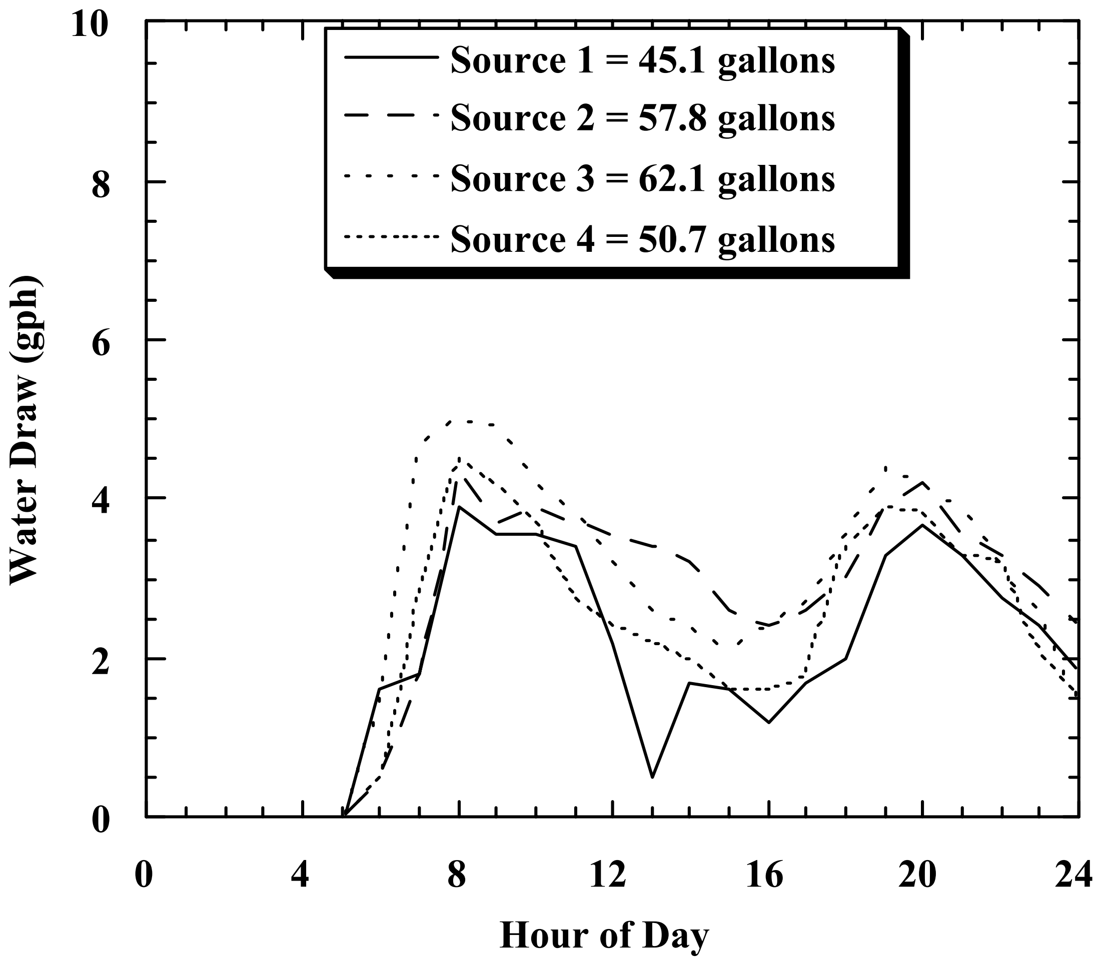

Figure 3.3.3: Average Daily Hot Water Usage (Pontikakis, 1994)

Source 1: 600 Single family homes across Canada (Stevenson,1983)

Source 2: Five residences in the Toronto area and fifty more residences located throughout the province of Ontario (Perlman et al., 1984)

Source 3: 110 single family residences by 11 utilities scattered throughout the continental United States (Ladd and Harrison, 1985)

Source 4: 18 single family residences located in Florida and North Carolina (Merrigan, 1988)

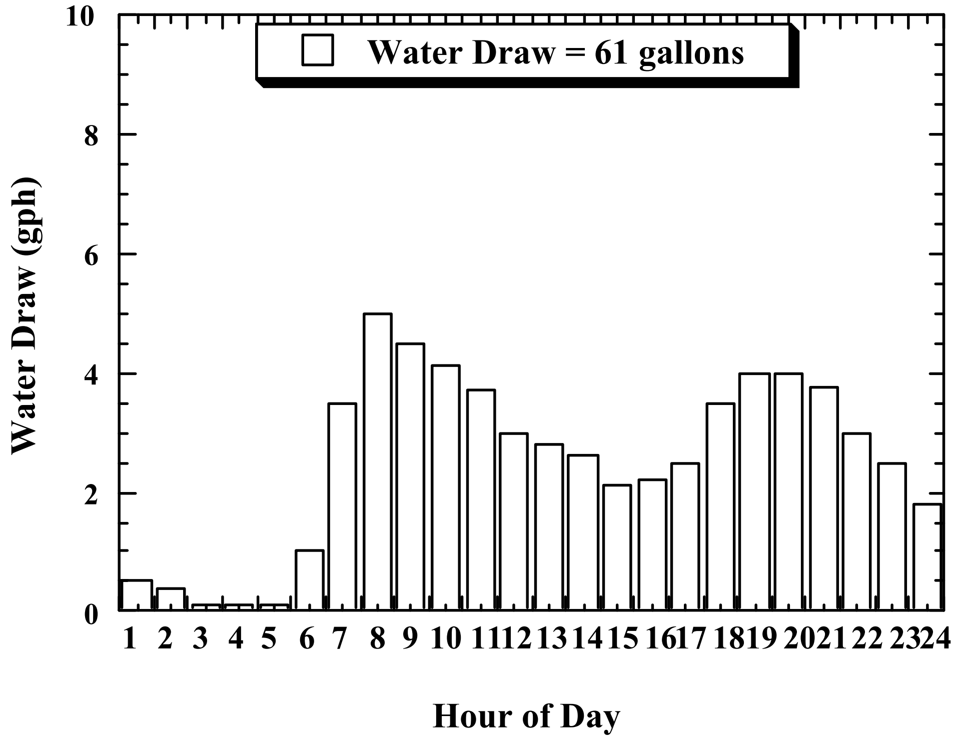

Figure 3.3.4: Average Hourly Hot Water Use for All Families (Becker, 1990)

Figure 3.3.4, representing the average hourly hot water usage for all families, is another one of the average profiles investigated by Grater (1992). The magnitude and timing of the draws show some similarities to the four compared in Figure 3.3 3.

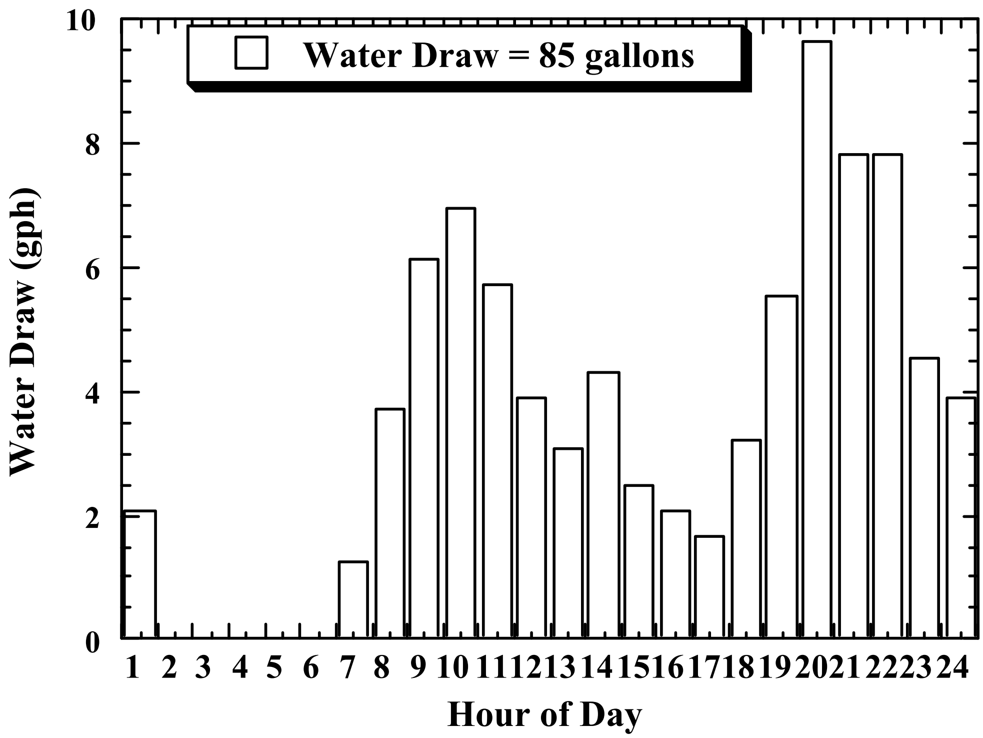

Figure 3.3.5: RAND Load Profile (TRNSYS, 1994)

The RAND (Mutch, 1974) profile is another average water use that is widely referenced and is shown in Figure 3.3.5. TRNSYS uses the RAND profile in Type 23, domestic hot water heater analysis. The F-chart Method was developed with this load profile. Although the amount of daily hot water usage varies in these profiles, the incidence of the hot water draws is similar to the WATSIM derived average weekday hot water draw. To compare the incidence of the six average profiles on a consistent basis, they were normalized in Figure 3.3.6. Except for the RAND peak in the afternoon, the magnitudes and timing of the hourly hot water draws are in surprisingly good agreement. The similarity of the draws lends support for the WATSIM derived average draws chosen for the DHW system analysis in this thesis.

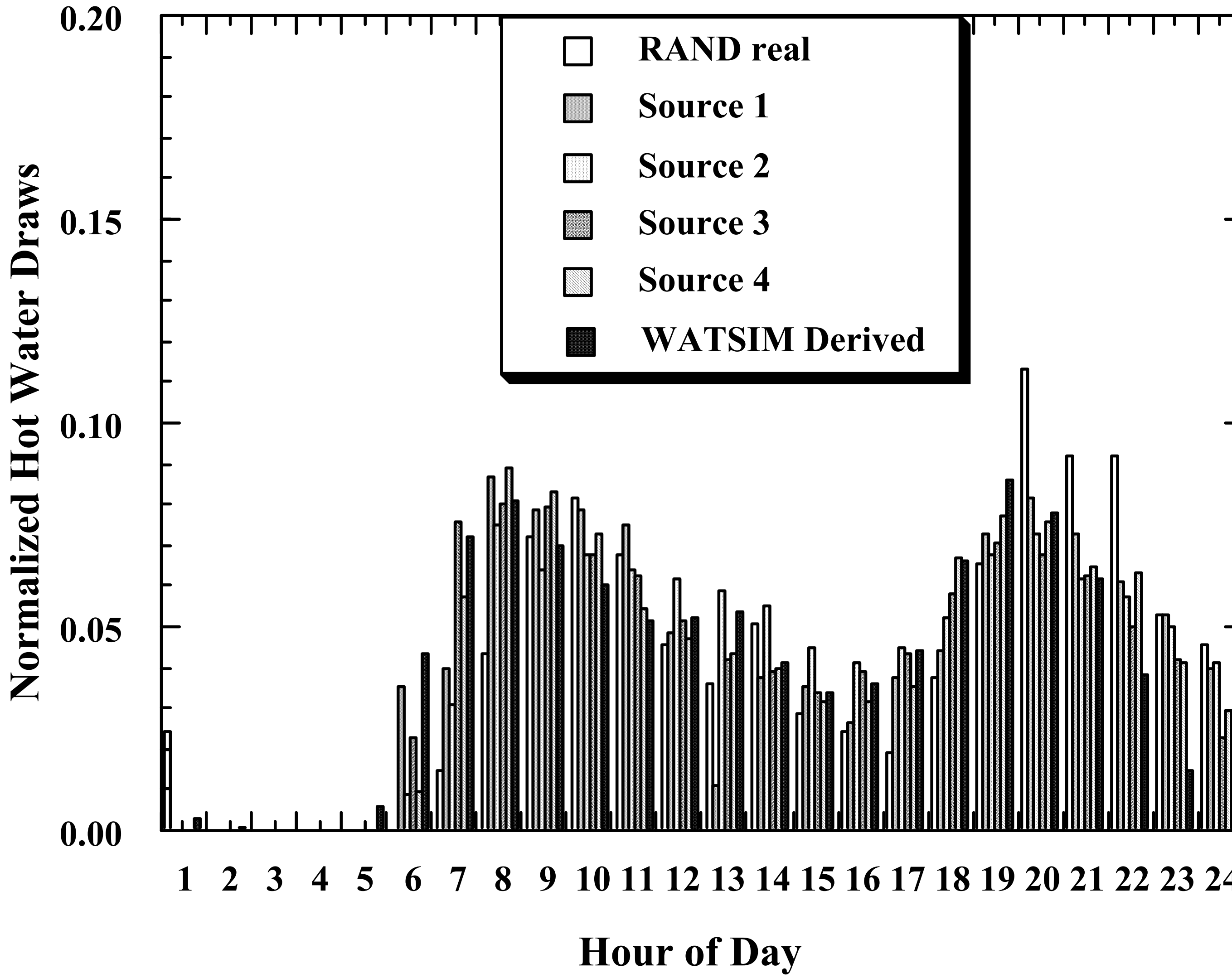

Figure 3.3.6: Normalized Hot Water Draws Compared

Figure 3.3.6 shows that the timing of the six normalized hot water profiles is relatively consistent. In Figure 3.3.7, the comparison of the normalized Wisconsin weekday average hot water draw profile with both the WATSIM and the RAND profiles shows dramatic timing differences. The Wisconsin profile, which has a questionable sample size and statistics, has a significant shift towards earlier morning draws (with a significant average draw at 4 a.m.) and a relatively constant evening draw from 3 p.m. to 10 p.m. These patterns do not agree with any of the other studies.

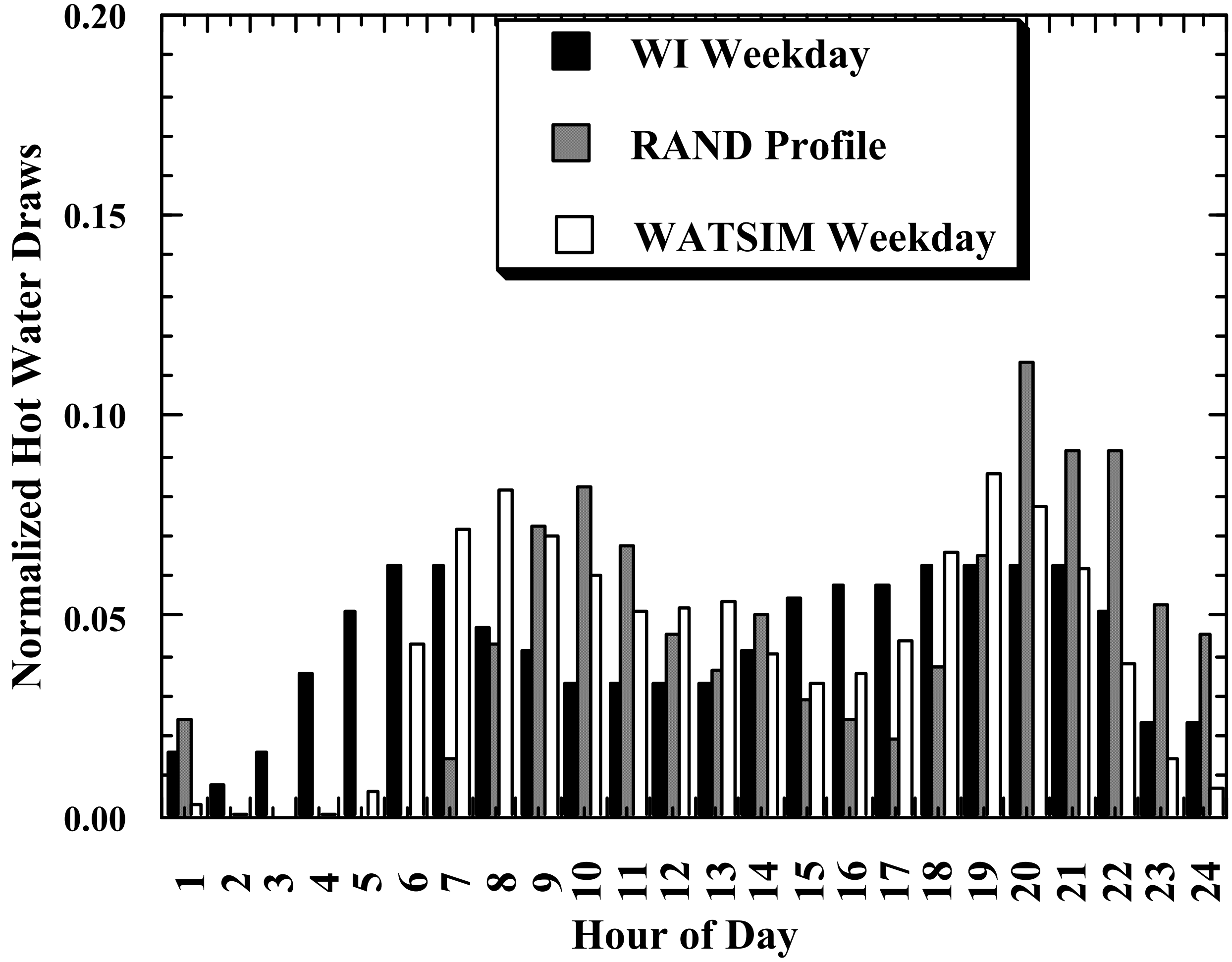

Figure 3.3.7: WI, RAND and WATSIM Compared (Normalized)

3.4 TRNSYS Simulation Model

TRNSYS, a transient system simulation program, was developed at the University of Wisconsin Solar Energy Laboratory in 1975 and has been continually modified and updated until the version 14.1 used in this thesis (Klein et al., 1994). Being a modular program, TRNSYS can simulate any type of solar, electric or fossil fuel-fired DHW system. The previous solar DHW and electric DHW studies performed with TRNSYS used the on/off 4.5 kW heating element electric tank, Type 4. Type 4 models the performance of real electric hot water tanks. This modeling, with on/off behavior is what requires the large number of runs (with different individual hot water draws) to create the average diversified demand of utility interest. The on/off heater has elements that turn on at full capacity (typically 4.5 kW) until the set temperature is reached, then turn off.

F-Chart has another model for electric DHW systems that uses energy rate control with an auxiliary heater (referred to as a zip heater in this analysis). Based on a temperature difference (see equation 3.4.1), the zip heater (Type 6 in TRNSYS) adds the amount of energy needed to maintain the set temperature. The amount of energy required from the auxiliary heater is determined by:

$$\int_{time} [(\text{mass flow to load})(C_P)(T_{OUT} - T_{MAINS})]dt \qquad \textbf{3.4.1}$$

T_{out} is the temperature of the water leaving the heater, and T_{main} is the temperature of the supply water from the mains.

Thus, the zip heater electrical demand directly follows the hot water draw. Intuitively, the same energy requirements will result through the zip heater as the on/off heater. But, can the same diversified demand be achieved with an average water draw with energy rate control, as with the average of hundreds of individual electric demands from hundreds of individual hot water draws with the traditional on/off heater analysis?

Although diversified average hot water draw profiles for weekdays and weekends have been obtained from WATSIM, modeling a single system with an average water draw does not produce the demand reduction achieved through a large number of varied, individual profiles, due to the on/off behavior of electric domestic water heaters. To evaluate the demand, energy, and emission reduction for a large number of solar domestic water heaters, it was previously thought that more than a thousand representative draws would have to be simulated on an annual basis with temperature level controlled DHW analysis. Hourly calculations for one DHW system for a year (8760 hours) with a diversified draw (1000 profiles) results in 8,760,000 simulated hours needed to analyze one type of solar water heater on an annual basis. Analyzing just ten different solar DHW systems, the resultant eighty-seven million TRNSYS simulated hours would take an unreasonable (over a year of Pentium runtime) amount of computational time to complete.

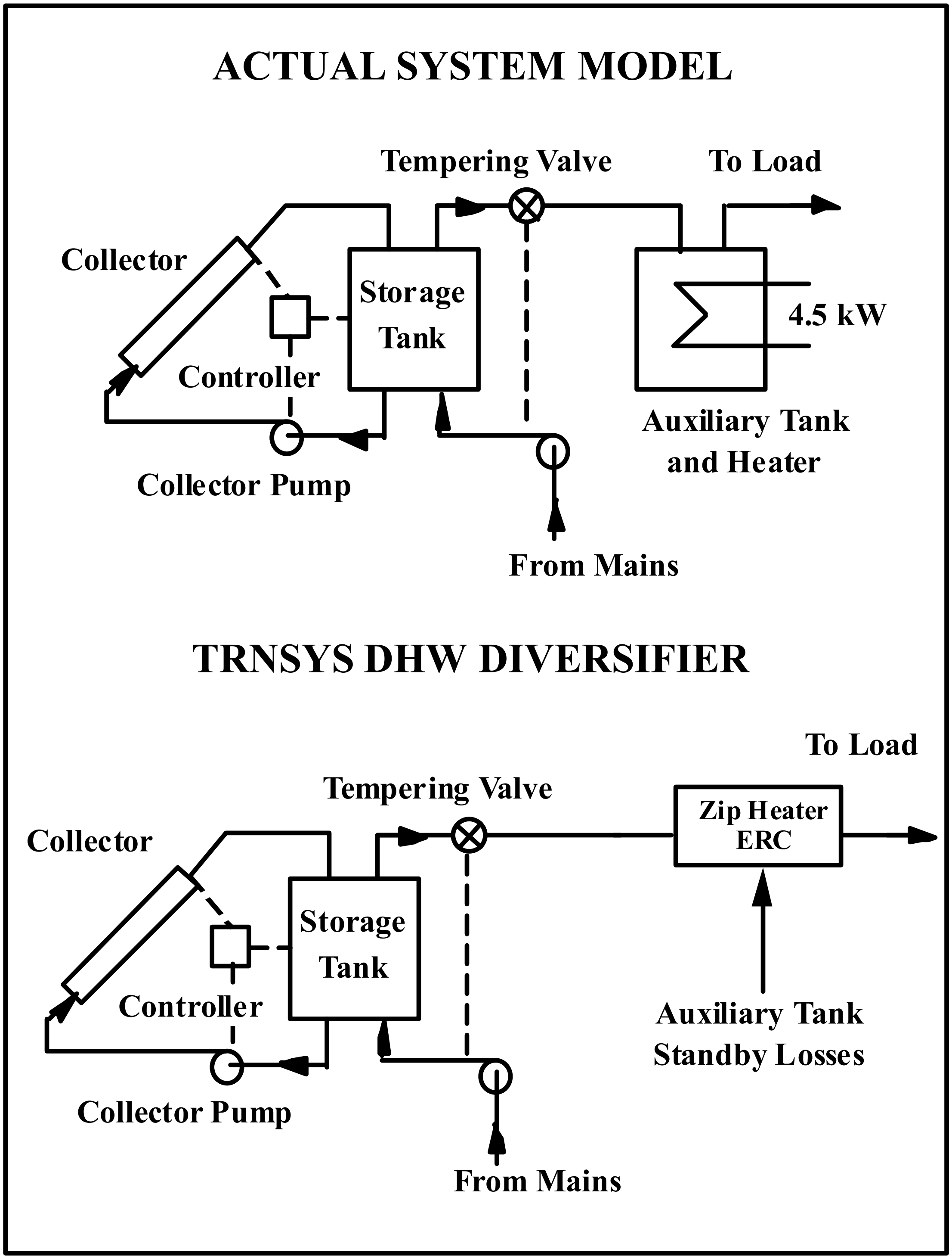

Figure 3.4.1: TRNSYS ZIP Heater Replacement

Using TRNSYS, the electrical load for an average water draw profile can be simulated with the same tank characteristics as for a typical 4.5 kW on/off electric water heater, but with one modification: the heating elements are removed and replaced by an energy rate controlled “zip heater". Both two-tank solar DHW models are represented in Figure 3.4.1. A one-tank model (with a heater that is one third of the way down) can be modeled with a storage tank of approximately 65% for storage of solar energy and the remainder electrically heated. In this application, a zip heater replaces the element that is normally in the upper one third of the tank.

Since a constant standby loss term is applied to the electrical demand of the auxiliary zip heater, the two-tank systems have a slightly higher electrical demand during high solar performance periods than a real on/off heater model with variable standby losses would have. During peak solar system performance, the back-up tank temperature could exceed the set temperature, partially compensating for the need for auxiliary energy when the tank temperature falls due to the tank losses. Unfortunately, the zip heater model does not reflect this behavior. Therefore, the auxiliary demand of a two-tank system is actually an upper limit for the possible demand during afternoon periods (peak solar system performance). The lower limit is zero demand during peak solar DHW performance.

Warren (1993) estimated that a single simulation using energy rate control (ERC) can predict the average of a large number (>1000) of thermostat controlled simulations. The zip heater approach is an efficient and accurate way to achieve the goals of this research (the calculation of annual emission, energy and demand savings and contribution to utility capacity). Not only does this method significantly reduce computation time, but it allows the user to experiment with a range of water draw profiles, various tank sizes, and different utility loads easily and without the necessity of knowing the details of the thousands of individual water draws.

3.5 Zip Heater Replacement

To test the accuracy of the zip heater model, a FORTRAN program (shown in the Appendix A) was written to produce one hundred "random" individual daily draw profiles from the average weekday hot water (ten minute interval) draw profile derived from WATSIM. Fifty gallons per hour during a ten minute interval is a realistic residential hot water draw. The following is a simplified example of the program. If there was an average draw of five gallons per hour at eight a.m., ten random numbers between one and one hundred would be chosen. Each random number corresponds to a profile number (customer) and, for each of these customers, the hot water draw at eight a.m. is set to fifty gallons per hour. All other customers (the other ninety numbers not chosen) are given a hot water draw of zero gallons per hour. Thus, when the hot water draws for all one hundred customers are averaged at eight a.m., the result is five gallons per hour. This process is repeated for ten minute periods of the average daily water draw profile, thereby creating one hundred individual profiles. When these individual hot water draws are averaged, the exact original average hot water draw results. The actual process is a bit more complex in order to mimic varying realistic water draw magnitudes. The average weekday draw profile and three of the hundred individual profiles are shown in Figure 3.5.1.

The energy and demand of an eighty gallon electric water heater tank were evaluated and are compared in Figure 3.5.2. The difference between the on/off heater model using the one hundred "random" individual water draw profiles and the zip heater with one single average water draw profile are tested through the four methods shown in Figure 3.5.2. Milwaukee weather from the third of day of hot sunny weather (coincident with WEPCO's 1991 peak demand day) was used for both Figures 3.5.2 and 3.5.3.

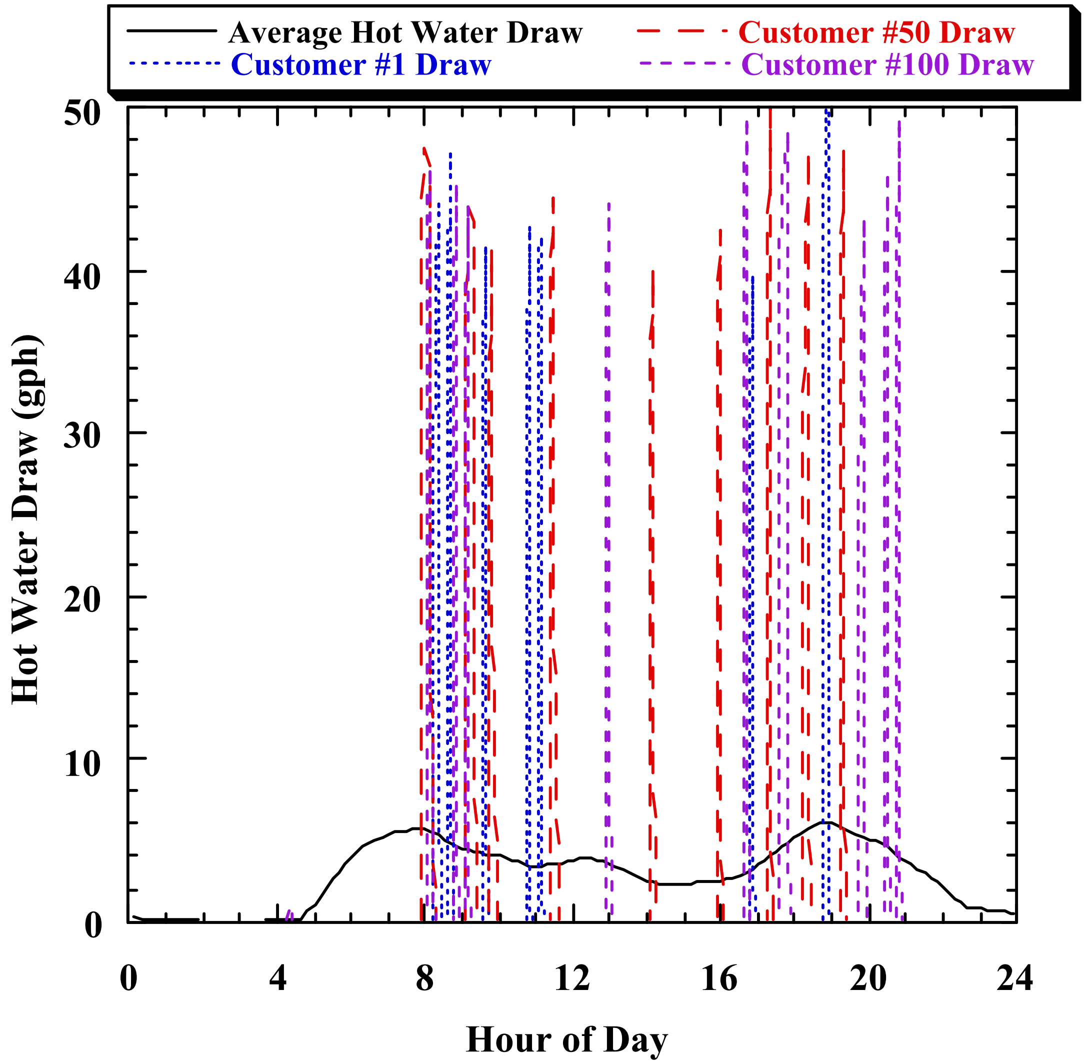

Figure 3.5.1: Random Hot Water Draw Profiles

Line A of Figure 3.5.2 is the electrical demand using the average daily hot water draw profile with a 4.5 kW on/off electric water heater. Line B is the average electrical demand of one hundred individual hot water draw profiles, each run for one day with the same 4.5 kW on/off water heater. Line C is the electrical demand for both (since they are nearly identical) the average daily hot water draw with an energy rate controlled zip heater and the average of one hundred individual draw profiles each run for one day with a zip heater. This graph shows that the computation of hundreds of individual hot water draws is unnecessary if a zip heater is used with the average hot water draw.

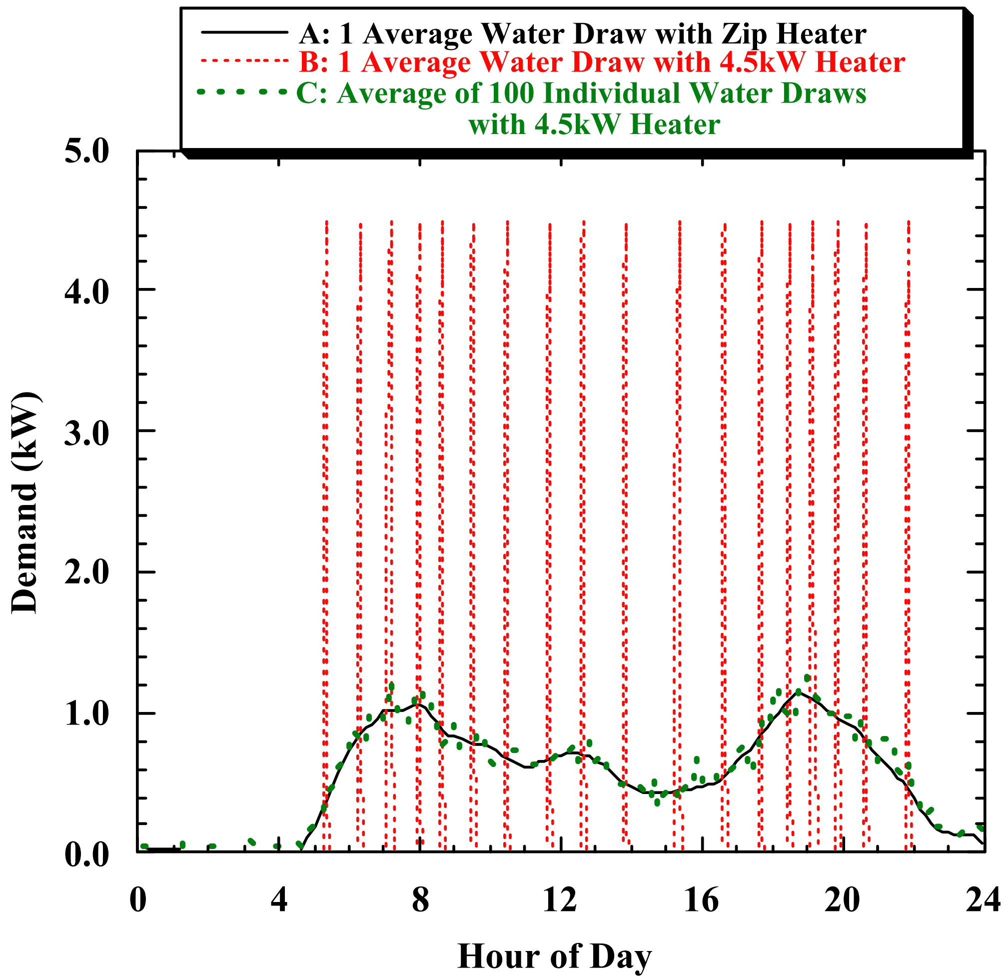

Figure 3.5.2: TRNSYS Demand Profiles for Electric DHW Models

Figure 3.5.2 shows that the zip heater can adequately model an electric only DHW system. This figure could also be considered a zero percent solar fraction system since there is all electric demand. The other limiting case is a one hundred percent solar fraction system, in which the electrical demand is zero. To test a mid-range case, a small (only thirty percent annual solar fraction) system was tested to confirm that this analysis can be effectively extended to solar DHW system analysis, as in Figure 3.5.3.

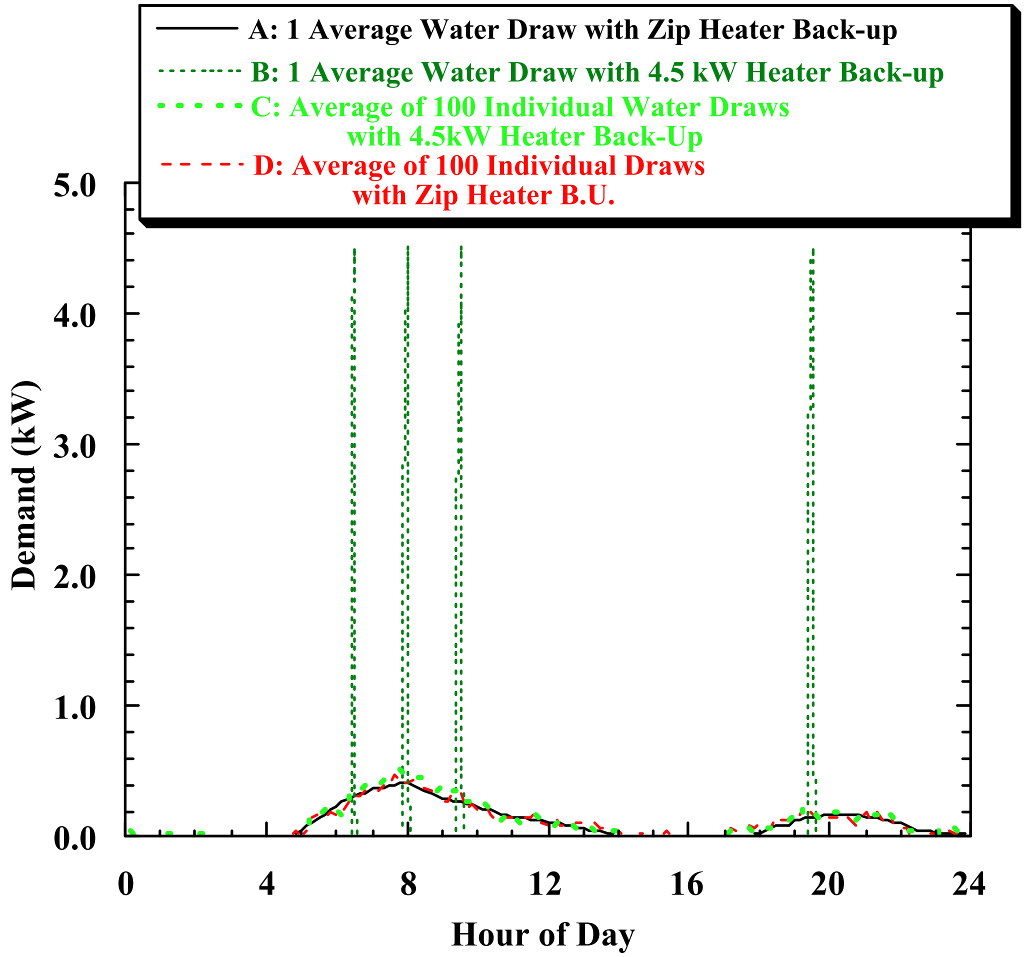

Figure 3.5.3: TRNSYS Demand Profiles for Solar DHW Models
Solar system: 2.5 m^2 collector panel area
With 80 gallon electric back-up tank (from Figure 3.5.2)
Solar Fractions: A: 79.5%, B: 76.6%, C: 78.3%, D: 78.3%

Line A of Figure 3.5.3 is the electrical demand using the average daily water draw profile with a 4.5 kW on/off electric water heater. Line B is the average electrical demand of one hundred individual water draw profiles, each run for one day with the same 4.5 kW on/off water heater. Line C is the electrical demand for the average daily water draw with an energy rate controlled zip heater and Line D is the average of one hundred individual draw profiles each run for one day with a zip heater. Line C is the conventional on/off method result, and Line A is the zip heater method. The difference in their solar fractions is less than one percent! As seen in both Figures 3.5.2. and 3.5.3, the zip heater method is shown to be a legitimate replacement for hundreds of on/off heater runs from both an energy analysis perspective and electrical demand.

One final test of the zip heater method and the "random" individual profile generator is shown in Figure 3.5.4. Five different sets of individual hot water draw profiles are used to calculated the average electric demand of the solar DHW system. The average of the five sets (5 times the average of 100 individual profiles) is also shown. Figure 3.5.4 demonstrates that the characteristics of the individual profiles used to create the average water draw are not significant. Thus, the average daily hot water profile can determine the average electric demand for solar DHW systems.

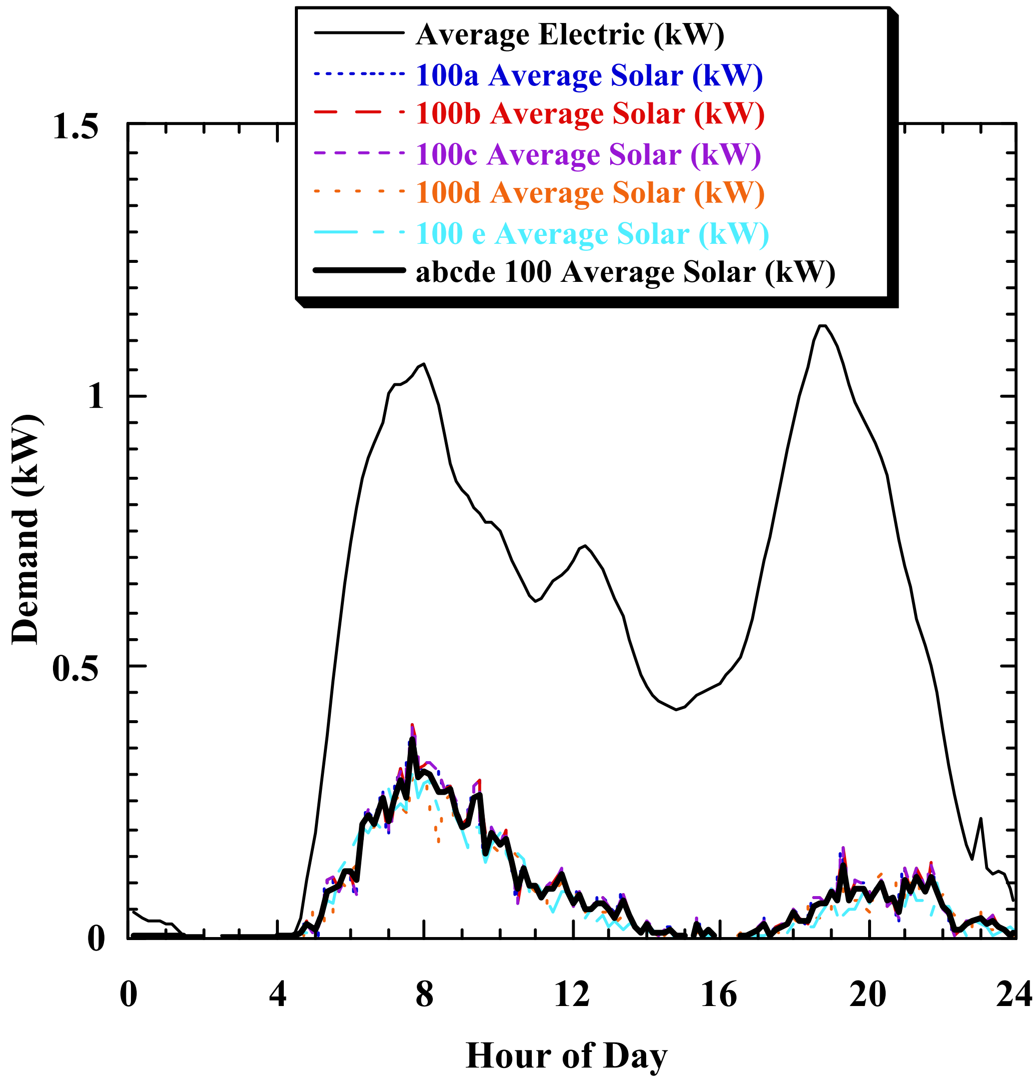

Figure 3.5.4: Electric Demand Comparison of Five Random Load Sets