3.0 SWAP PROGRAM EVALUATION

In order to quantify the value of the SWAP program, four separate methods were implemented to assess measured energy savings, quality of system installation and operation, and general perceptions of the users of solar domestic hot water (SDHW) systems. This collected information is intended for the following applications:

- As the basis for the implementation of this pilot program as a standard weatherization option (Department of Energy, 1993).
- To study the water usage characteristics of low-income owner-occupied housing.
- To evaluate the short-term reliability of solar water heating systems, and to collect data for future long-term reliability evaluation.
- As a study on the perceptions of the operation of SDHW systems.

Two methods were used to evaluate energy savings from the SDHW systems: "Hard Monitoring" and "Soft Monitoring." The hard monitoring method consists of a detailed monitoring of 35 systems for two years (pre and post solar), while the soft monitoring consists of the analysis of two years worth of utility bills for 275 households. The soft monitoring was performed in order to verify if the measured energy savings from the hard monitoring could be evaluated through the statistical analysis of household utility bills (which are sensitive to weather and many other things, including the solar system). The advantage of the soft monitoring is that it does not require the use of any additional monitoring equipment.

Two methods were used to evaluate the quality of installation and operation: inspections and surveys. Over 25% of the sites were inspected by FSEC staff after the installation of the SDHW system to ensure quality of installation and to field verify components used in the installation process. The surveys were mailed to all SWAP clients. Approximately 1/3 of the surveys were returned. Although the primary intent of the surveys was to gain information about the occupants and their perceptions about SDHW, there were also indications of installation issues as well.

3.1 SITE SELECTION CRITERIA FOR INSTRUMENTED AND SOFT MONITORING

In addition to the requirements for the solar weatherization sites, five additional requirements were imposed for the hard and soft monitoring sites in order to ensure that the data collected before and after the solar installation was as consistent as possible:

- The occupants must not have been planning an extended (greater than two weeks) stay away from their house during the monitoring period. A decrease in energy consumption during such a period might be erroneously attributed to conservation rather than lack of occupancy. Likewise an anticipated increase in occupants was also not anticipated during this monitoring period.

- During the two year SWAP monitoring period, the house must not have been scheduled to receive housing modifications under any other weatherization or housing rehabilitation program. This was to help ensure that the only change made to the house during the monitoring period was the installation of a solar system. This was done to ensure consistency in the house energy use characteristics for utility bill analysis.

- A required site inspection of the residence was conducted by FSEC staff prior to selection to ensure that the residence was suitable for the hard monitoring phase (this was not performed for all soft monitoring). Upon completion of the solar system installation, FSEC staff conducted an inspection to determine that the solar system was installed properly and that both the system and the monitoring equipment were functioning correctly. Installation and operation deficiencies were corrected before formal solar system monitoring for phase two (post solar) was initiated.

Selected homeowners were required to sign an agreement form stating that they were willing to participate in the SWAP monitoring program (for soft and/or hard) and authorizing FSEC to obtain past and present utility bills. This agreement also provides FSEC and solar installers permission to access the site as required for monitoring (hard monitoring only), installation, and maintenance purposes. All hard monitoring sites were also incorporated into the soft-monitoring program so that monitored and predicted savings could be compared.

The monitored sites were selected so that the regional (North, Central, and South) number and system type were roughly proportional to the number and type of installed systems.

Although efforts were made to enforce these additional requirements to maintain a high quality of measured data, feedback from the homeowners indicated that in some cases, these rules were not maintained. One of these (discussed in the soft monitoring section) is that some WAP measures besides solar were implemented in these homes during the two year moratorium on these modifications, possibly affecting the quality of the soft monitoring data.

3.2 OVERVIEW OF COLLECTED DATA

A variety of data were collected in order to satisfy the requirements of the program evaluation.

Table 3.2-1 summarizes the types of data which were collected, the way in which each type was collected, and the phase(s) during which each was collected.

Table 3.2-1. Summary of Collected Data

Data Type	Phase One (Pre Solar)	Phase Two (Post Solar)
Total electric use	Electric bills	Electric bills
Occupancy	Surveys	Surveys
Solar system reliability	N/A	Site inspections, surveys
Hot water system operation	Monitored data	Monitored data, site inspections, surveys
Owner satisfaction	N/A	Surveys
Operation and maintenance	N/A	Surveys, site inspections
Local temperature (at location of water heater)	Monitored data	N/A
Pump and controller power measurements	N/A	Site measurement
Regional weather data	Local meteorological station	Local meteorological Station

Information was gathered through system inspections and surveys pertaining to system operation, owner satisfaction, repair requirements, failure rates and frequency, types of failures, criticality of failures, and general degradation of components. Survey data was used to document the number of occupants and their impacts on energy use, specifically for water heating. All of the survey and inspection data were summarized and incorporated into a database for analysis and future retrieval.

A separate database (in-house format) was used to store and analyze monitored data. The local meteorological data and utility billing data were stored in ASCII files used for analyzing this data.

4.0 HARD MONITORING

The primary purpose of the SWAP monitoring project was to determine the energy savings and cost effectiveness of low-cost solar water heating systems in low-income homes in Florida. This will determine the feasibility of incorporating solar water heating systems as a WAP program weatherization measure. Ancillary SWAP monitoring program purposes and issues also addressed include:

1. Determining the savings-to-investment ratio (SIR)
2. Evaluating the reliability of SWAP installed low-cost solar water heating systems
3. Comparing hot water usage and associated energy costs before and after solar system installations
4. Determining low-income hot water usage profiles

The purpose of this monitoring project was not to once again ask if solar water heating works, but instead to ask if it is cost effective for the WAP program and low-income families. With this in mind, the monitoring program was developed by FSEC in an attempt to provide statistically significant data necessary to answer this question while keeping costs of monitoring to a minimum.

The hard monitoring phase of the SWAP program was intended to provide quantitative evidence regarding the performance of a representative sample of installed SDHW systems. The results from this phase of the work indicate the viability of the systems both in terms of thermodynamic performance as defined by Coefficient of Performance (COP) and economic savings for the US Weatherization Program's National Energy Audit (NEAT) procedure as defined by the SIR (Gettings, 1990). Additional information, including water usage profiles, average water temperatures and monitoring-related issues have also been gleaned from the data.

A total of 35 systems were selected for the hard monitoring phase. Sample size was kept small to minimize costs. A sample size of thirty was considered to be sufficient for the purposes of this study. Therefore, a sample size of thirty-five was chosen to allow for unforeseen circumstances which could result in the elimination of test houses. Selection was based on the first thirty-five houses that met the criteria set forth previously. Two of the sites (#2 and #30) were dropped from all analysis due to unanticipated ownership changes. A third site (#10) was also dropped due to a fire that caused the house to be vacated during 6 summer months of the post solar monitoring period. A total of 32 sites were used for the overall hard monitoring analysis. As explained later, some of these 32 sites were not included with some of the comparisons (e.g., F-Chart) due to lesser problems that did not preclude them from the overall analysis.

Each test house was located in one of the three climate zones. While the North was represented in the total sample, the distribution of test houses was more consistent with population demographics. Specifically, the majority of the test houses were in Central and South Florida. Local WAP agencies in each of these regions were identified to assist in selection of these houses.

Southern Florida was represented by Dade County. Mid-Florida (Hernando County) and Citrus County represented Central Florida. Suwannee and its surrounding counties represented Northern Florida. (See Florida Map in Appendix 4.)

Because water usage and weather vary throughout the year and the efficiency of the solar system is a function of both the load and weather, a period of one year after the solar installation was selected as the second monitoring period. In this way typical annual extremes of load and weather would be accounted for. Although the existing electric auxiliary tanks are less sensitive to weather changes than the solar systems are, a period of one year was also selected for the pre-solar installation. This method, although considerably time consuming, gives the most credible indication of savings, assuming that the household has consistent water usage patterns.

4.1 HARD MONITORING: INSTRUMENTATION

The instrumentation for this project was designed to yield adequate information for calculating the COP, SIR of the SDHW systems and the water usage patterns of the households. To accomplish this, a moderate amount of hourly (or better) data is required, as indicated in DOE's Single-Family Building Retrofit Performance Monitoring Protocol (Ternes, 1987). Other information was also extracted in this process.

In order to calculate hot water energy delivery, the following measurements are required: inlet temperature, outlet temperature, and flow rate. To calculate efficiency of the existing electrical tank, the electrical energy input is also required. Additional information acquired during the pre-solar phase included the environmental temperature at the tank and the horizontal radiation gathered on the roof. Because the radiation value was only to be used for diagnostic purposes and the installed angle of the solar collector was not known at the time of sensor placement, a horizontal measurement was used.

During the post-solar phase, the collector feed and collector return temperatures were added and the ambient temperature was removed (due to lack of additional channel space on the datalogger). These two quantities, along with the solar radiation were used primarily to identify and resolve problems with the systems. For some of the active systems, these values were also used for predicting pump and electric valve operational times. Because no real-time pump and valve power were measured, a one-time site visit was made to measure the wattage of the pump and electric valve in all of the systems employing pumps and electric valves. Table 4.1-1 indicates the type of instrumentation used for the systems. Appendix 5 contains the specification for the instrumentation. Table 4.1-2 indicates the site-measured values for the pump/valves. Notice that sites #22 and #29 had significantly higher measured power consumption (for controller, pump, and electric valve) than did the other sites with similar equipment. Since the piping runs and equipment are similar, it is unclear why these values differ.

Table 4.1-1. Instrumentation

Measured Quantity	Device Type	Accuracy	Manufacturer and Model
Temperature	Thermocouple (Type T)	+/- 1.5 ° F	Any Copper-Constantan
Flow Rate	Positive Displacement Flow Meter	+/- 1.5 %	Kent Meters Model C-700
Electrical Energy	Watt-hour Meter	+/- 2 %	Hialeah Meter Model D4S
Radiation	Semiconductor-Based Pyranometer	+/- 5 %	Licor LI-200SB
Pump/Valve Electrical Power	Digital Power Analyzer	+/- 0.25% +/-6 counts	Valhalla Scientific Model 2101

Table 4.1-2. Measured Pump/Electric Valve Wattages

Site Number	Collector Pipe Run (Feet)	Pump	Controller	Electric Valve	Measured Wattage
22	17	Grundfos UP-15-18 B5	Goldline GL-30-LCO	Erie 5/8 SWT MOPD	89
24	14	Grundfos UP-15-10 B5	Goldline GL-30-LCO	Honeywell V4043A	43
25	17	Grundfos UP-15-18 SU	Goldline GL-30-LCO	Erie 5/8 SWT MOPD	56
26	18	March 809-2	Intermatic Timer	N/A	26
28	20	Laing SM 3CB BSW	Heliotrope Delta T	N/A	43
29	23	Grundfos UP-15-18 B5	Goldline GL-30-LCO	Erie 5/8 SWT MOPD	85

31	18	March 809-2	Intermatic Timer	N/A	27
32	20	Grundfos UP-15-18 B5	Goldline GL-30-LCO	Erie 5/8 SWT MOPD	56
33	24	Grundfos UP-15-18 B5	Goldline GL-30-LCO	Erie 5/8 SWT MOPD	57
35	36	Grundfos UP-15-18 SU	Goldline GL-30-LCO	Erie 5/8 SWT MOPD	57

Placement of the instrumentation is critical to the proper understanding of the systems' performance. The ideal placement of the sensors is indicated in Fgure 4.1-1. The placement of the inlet sensor (cold water) was the most difficult to make due to limited access. Due to conductive effects and unanticipated in-line thermosiphoning, it was necessary to relocate this sensor at several sites and adjust the data acquisition program accordingly. The other temperature sensors would also be affected by the same effects, although the collector feed and return could usually be located further from the tank and conduction in the hot water usually improved response time, as opposed to reducing it for the cold inlet.

Error! No topic specified. Figure 4.1-1. Placement of Instrumentation for Hard Monitoring – Timer System

The placement of the flow meter was made in the cold inlet directly before the tank for two reasons: the flow meter is not designed for temperatures in excess of 120° F, and the desired flow was into the tank, not into the system. In all installations, the flow meter was further protected by the use of a heat trap in the cold water piping. Because many of the SDHW systems use an anti-scald valve, the cold flow rate before the "T" to the valve may be higher than the flow through the tank. The tank flow was used to isolate the mixing valve effects from the measurements; however, this method necessitated the addition of a check valve before the anti-scald valve in the cold water line to eliminate the thermosiphoning in this loop that sometimes resulted.

4.2 HARD MONITORING: DATA COLLECTION

Because all of the sites are located at some distant from FSEC, a datalogger with remote data transfer capability was required. Additionally, the instrumentation outputs and a desire for data storage were initial considerations in choosing the data acquisition system (DAS). A Campbell CR10 datalogger was selected because of its reliability and capability to be easily used in remote applications. The DAS box consists of the datalogger, modem, battery, electrical connection, and phone connection. A diagram of the DAS box is included in Appendix 6. The datalogger has ample storage and battery capacity to operate without losing data for at least a week when no power or phone line connection is available. A separate phone line was installed at each site so that the data could be uploaded to the FSEC VAX computer system on a daily basis without the need for periodic visits.

Software developed at FSEC was used to poll each site on a daily basis to retrieve, store, and process the data. A co-current program, SWAPA, was developed to analyze the data from the sites on a daily basis. For each site, the program lists Inlet Temperature (CW), Outlet Temperature (HW), Feed Temperature (FD), Return Temperature (RT), Radiation (SOL), Total Flow (FLOW), Calculated Energy Delivered (Btu), Measured Input Energy to Tank (kWh), and Calculated COP. A status variable by each measurement is used to flag any problems. "O" =ok, "-" = Low, and "+" = High. Missing or calculations that can't be performed are flagged as 999.99. Table 4.2-1 indicates the bounds for flagging the data.

Table 4.2-1. Flagging of Data for Daily Quality Check

Quantity	Adjustments	Low ("-")	Okay ("0")	High ("+")
Cold Water Temp.	Average for flows > 1 gallon / 15 minutes	< 50° F	50-90° F	> 90° F
Hot Water Temp.	Average for flows > 1 gallon / 15 minutes	< 80° F	80-130° F	> 130° F
Feed and Return Temps. (Active	Average for flows > 1 gallon / 15 minutes	Return< Feed	Feed>= Return	N/A

Solar Systems)				
Feed and Return Temps. (Passive Solar Systems)	Average from 8 AM to 5 PM	Return< Feed	0°F< (Return-Feed) < 20° F	(Return-Feed)> 20° F
Flow	Sum all day	< 10 Gal.	10-150 Gal.	>150 Gal.
kWh (Element)	Sum all day	N/A	All others	KWh>15 kWh or kWh/Flow> 0.1
COP	Calculated (Sum Btu/ Sum kWh)	0.8	0.8-10.0	>10.0

Although many data errors were caught using the status variables indicated by this program, others were not clearly detected by daily calculations. Consequently, visual graphs of all system outputs on a site-by-site basis were also plotted on a daily basis to catch other problems. A sample of these graphs and the output of the daily quality check program are provided in Appendix 7.

4.3 HARD MONITORING: PROBLEMS WITH DATA COLLECTION

Although every effort was made to ensure the highest quality of collected data, there were several cases where the data was corrupted and/or problems with the system occurred. These discrepancies had to be cleaned up before the final analysis could be performed. The first step was the identification of problems in either the DAS or in the water heating system. As indicated in the previous section, this occurred on a daily basis. A log sheet was maintained for each site to track problems. Appendix 8 contains these log sheets for all sites.

Upon identification of problems, appropriate steps were taken to remedy problems. In many cases, the problems were obvious and the solution was clearly enacted; however, in some cases, the solution proved elusive, and the true cause of the problem was never really determined. Table 4.3-1 indicates some of the more significant monitoring related events that occurred.

Table 4.3-1.Significant Monitoring Related Events

Event	Affected (%)	System Type Affected	How Resolved
Major kitchen fire.	6	All	Data excluded, 1 site dropped.
Unanticipated occupancy changes.	20	All	Occupancy was adjusted, 2 sites dropped.
Temporary air entrainment in ICS systems at startup caused false flow indications.	80	ICS	Data excluded for the first 1-3 weeks of solar operation. The only effect upon the system operation is some initial turbidity in the delivered hot water.
Short circuiting of water through anti-scald valve.	67	All active 50% of ICS	Water mains temperatures from pre-solar operation used as required. Check valve installed to prevent this. The original system design did not include this feature.
Bottom feed/return on tanks crimped.	25	Timer controlled	Data excluded and bottom feed/return was replaced. Problem was due to poor installation.
Systematic loss of thermocouple data.	14	All	Data excluded and additional grounding installed.
Problems with datalogger phone line.	37	All	Phone line repaired.
Power turned off	9	All	Power turned back on.

unintentionally.			
Major household leak (> 4 gal/hour).	23	All	Data excluded and leaks fixed. These problems were not related to the solar system.
Cold water temperature increases with flow due to routing of cold water line through attic/exterior masonry walls, which preheats water.	14	All	No adjustment necessary - this is an actual usage condition that existed prior to monitoring.

Prior to the commencement of the data analysis, the third step of data clean up was performed. All of the bad data from the daily logs were flagged and a sample of the raw data was visually inspected (at times most likely to be bad) such as when monitoring started or the solar system was first installed) to locate any further problems. These bad times for data were used as input for the data analysis step.

4.4 HARD MONITORING: DATA REDUCTION AND ANALYSIS

With the completion of the monitoring phase of the project in April 1998, data had been collected for a period of approximately two and a half years. The final collection period was extended by several months to overcome some of the problems indicated in Table 4.3-1, which resulted in several months of lost data for sites #17, #26, and #31.

Based upon the problems gathered in the daily monitoring phase, the data were cleaned up to eliminate the following type of problems:

Missing data (flagged automatically by FSEC's data reduction software). These data were ignored.
Data that exceeded normal ranges (flagged automatically by FSEC's data reduction software). This would include thermocouple grounding problems. These data were ignored.
Abnormal occupant absence: data ignored.
Abnormal utility cessation: data ignored.
Initial monitoring and/or water heating installation errors: data ignored.
DAS failure and/or sensor failure: data ignored.
Small hot water leaks (< 4 gal/hr): These data were kept, as it was felt that small leaks would not be fixed on a routine basis due to limited funds/capability on the part of the homeowners.
Large hot water leaks (>=4 gal/hr): These data were ignored, as it was felt that that these size leaks would normally be fixed.
Misplaced sensors: data ignored.
Inaccurate cold water sensor: Pre-solar water temperatures used instead.
Dataloggers inadvertently programmed in both standard and daylight savings time: adjusted in software.

With consideration of the listed methods of eliminating some of the bad data, a program, FINAL, was written that interfaced with FSEC's GET V3.0 software. The GET software accesses the database created by the daily polling of the data. The FINAL program processes these data so that the desired output is created and unwanted/bad data are eliminated.

Additional processing of the data was also performed to clean up some of the values and to generate calculations not explicitly measured. Because of problems with mixing valves and the resulting unanticipated thermosiphoning, all of the active systems that had problems with cold water temperatures used averaged data from the pre solar operation for the time period preceding the addition of the check valve. Additionally, because most of the systems exhibited some problems (due to conduction from tank) with the cold water temperatures, an algorithm was incorporated that uses the most recent cold water temperature that occurred during flows of 1 gallon or more per fifteen minutes.

Although the measured flow temperature was used for energy calculations, the calculation of load profiles was complicated by the presence of the anti-scald valve. The anti-scald valve was assumed to be an ideal mixing valve set at approximately 122° F, which allowed for the determination of the total hot water load that was delivered to the household. This value was only used for the determination of water usage profiles and reporting of average water usage.

Because the DAS did not measure power use of the controller, electric valve (used in place of a manual check valve), and pump, the one time measurements were used, along with an algorithm to predict 15 minute energy usage. For passive systems, this number was equal to zero. For timer systems, this value was a fixed value for 9 hours per day, which was consistent with the settings. For the differential controlled active systems, the algorithm looked for several things to determine if the collector pump was operational (when off, the power draw was assumed to be 1.6 W):

> Can only operate from 7 AM to 8 PM.
> Return temperature-Feed temperature> 0.5.
>
> The change in feed temperature/time is > 6° F/hour and the change in feed temperature/time is > 6° F/hour if the pump is off.
> The change in feed temperature/time is > 2° F/hour and the change in feed temperature/time is 2° F/hour if the pump is on and flow =0 or flow>0.

Although an attempt was made to validate this algorithm by the use of a clip-on datalogger, it yielded no useful data. Comparison of this algorithm and visual temperature data yielded good agreement.

From the raw data, the FINAL program calculates several quantities that are used for further analysis. Calculation of energy delivered to the load is by the standard formula:

$$\text{Q Delivered} = M * C_p * (\text{T out} - \text{Tin})$$

Where Q Delivered is the water-heating load, M is the mass flow rate, Cp is the heat capacity of the water and Tout and Tin are the outlet and inlet temperatures of the storage tank. The figure-of-merit for solar water heating systems, like many other appliances is the COP:

$$\text{COP} = \frac{\text{Q Delivered}}{\text{Q Aux} + \text{Q Parasitic}}$$

Where Q Aux is the energy used by the electric element and Q Parasitic is the energy used to power the pumps, controllers and valves of the solar system. For passive and photovoltaic-pumped solar systems and all of the systems prior to the addition of the solar component, Q Parasitic = 0.

This program was used for the calculation of several quantities for both a monthly and time of operation basis. Appendix 9 includes a monthly summary of all systems during both the pre- and post-solar installation periods. The data in this appendix was used for monthly comparisons and for the comparison with F-Chart. The following list summarizes the information presented in the first page of each monthly table:

> Site: Site number
> Cold (F): Average cold water temperature.
> Hot (F): Average hot water temperature.
> Flow (Gal): Total flow.

Aflow (Gal): Adjusted flow (includes anti-scald valve flows).
Load (MMBTU): Water heating load.
Elem (MMBTU): Q Aux – Auxiliary energy used by electric element.
Par (MMBTU): Q Par – Calculated energy used by pumps, controllers, and electric valves.
Rad (kBTU/sf): Average amount of solar radiation per horizontal surface area.
COP: Coefficient of Performance
Eff (%): A rough measure of solar radiation converted to hot water energy. Used for diagnostic purposes only. This value is zero except during months in which solar was installed at the start of the month.
BTU/GAL-DT: A calculation determined by dividing load by flow and the difference between hot and cold.
Good %: Indicates percent of hours in month that data were good. The basis for 100% may be less than the number of hours in the month if the system monitoring was completed during the month.
Good (hr): Number of good hours. This excludes flagged, missing, bad and excluded data.

Note that missing data and/or invalid calculations are flagged with 999.99.

Appendix 10 contains a different summary of these data for each site. Each site has two listings, a pre solar listing and a post-solar listing. A spreadsheet was created from the data in Appendix 10 to create the overall evaluation of the program. The following calculations for SIR and Solar Fraction were also performed at this stage:

$$\mathrm{SIR} = \frac{\mathrm{Savings} * \sum \dfrac{\mathrm{Fuel\ Cost} * \mathrm{Fuel\ Price\ Index}_{\mathrm{I}}}{(1 + \mathrm{Discount\ Rate})^{\mathrm{I}}}}{\mathrm{Installation\ Cost}}$$

For the SIR calculations, the data in Table 4.4-1 were used. Note that energy costs were based upon an amount that the customer could save. In general, this will be less than the total cost of electricity because the customer charge (fixed) is not included. The current implementation of the SIR for the NEAT program does not include additional maintenance costs. These costs have not been included in the SIR calculation to allow the solar performance to be evaluated on an equal basis with other measures (some of which may also require maintenance). Estimated maintenance cost could well be $150 for each active system every 10 years and $100 for each passive system every 10 years. These average costs would include system service and one component replacement.

Table 4.4-1. SIR Calculation Assumptions

Parameter	Value	Source
Life Time	20 Years	General assumption
Fuel Price Index	Varies from 1.0 in year 1 to 0.93 in year 20	Energy Price Indices and Discount Factors for Life-Cycle Cost Analysis-April 1997 (Fuller 1997)
Energy Savings	Varies by site	Measured SWAP data
Installation Costs	Varies by site	Actual Installation costs
Discount Rate	4.7%	Energy Price Indices and Discount Factors for Life-Cycle Cost Analysis-April 1997 (Fuller 1997)
Fuel Cost	$0.08/kWh	Average of variable user electrical costs (energy, fuel, and taxes) for 94% of the Hard Monitoring sites.

The Solar Fraction (SF) compares the portion of the normalized pre-solar energy with the post-solar energy to deliver the water load and overcome standby losses.

$$SF = 1 - \frac{Q\ Aux\ Post\ Solar + Q\ Parasitic}{Q\ Aux\ Pre\ Solar}$$

4.5 HARD MONITORING: OVERALL RESULTS

Site-By-Site Calculations for the pre- and post-solar time periods were performed on measured values, energy flows, power demand, and water usage profiles. A spreadsheet was used to calculate and display the summary results from these data. Monthly comparative calculations were made on measured values, energy flows, and water usage profiles. A second spreadsheet was used to calculate and display monthly comparative results from these data.

For measured data, the adjusted values (as indicated previously) were averaged/totaled as appropriate.

For the energy calculations, the data were normalized to an annual time period (monthly for the comparative results) and to the actual number of systems operating. Because the delivered hot water load fell by approximately 7% between the pre- and post- monitoring phases, the energy calculations used to project energy savings and SIR were normalized to the average of the pre-and post- hot water loads. Note that the energy calculations used for the Soft Monitoring and the F-Chart comparison were not adjusted to the average pre and post solar load.

For water profile calculations, the 15-minute water consumption per site were summed together to create an hourly consumption per site. The data from all sites were summed together and binned on an hourly basis. The reported fractional profile was generated by dividing the hourly usage by the total usage for 24 hours.

A Comparative monthly illustration was performed on a subset of the final data to provide an illustrative example of the solar system performance. These calculations were performed one year apart on a monthly basis for all of the systems in operation at the time. The months of October through December were not included because most of the installations occurred during this period and the combination of start-up problems and relatively few number of systems in operation could have skewed the comparison.

Figure 4.5-1. indicates the monthly reduction in energy usage by the solar systems. The energy usage indicates a large energy reduction and illustrates that the water load falls by approximately 1/3 during the summer months.

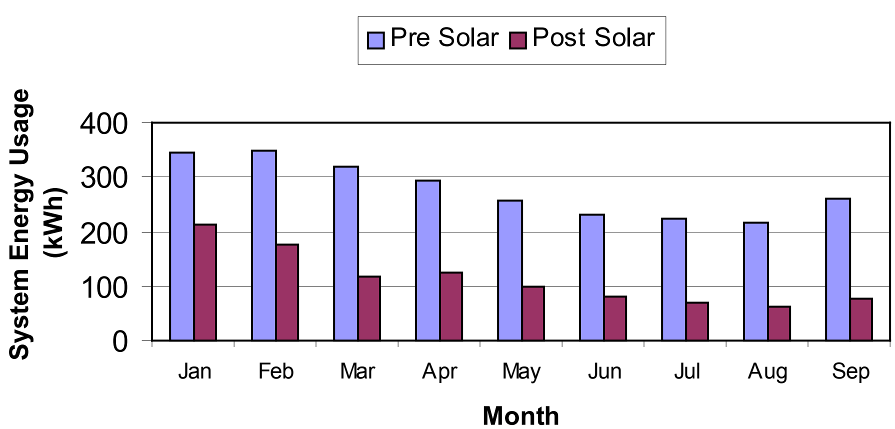


Figure 4.5-1. Monthly Pre and Post Solar Total Measured System Energy Usage

The following graphs and tables indicate annual calculations. Figure 4.5-2. indicates the measured annual water usage profile. In contrast to the "Florida Average" profile (Merrigan 1988), which has a dual peak in the morning and evening, this profile exhibits a relatively flat profile during the day with the main peak at night (rather than in the morning in Merrigan's work). Merrigan's profile is similar to the profile that generally is used for national consumption analysis (Becker and Stogsdill, 1990). What this indicates is that the home is usually occupied during the day with primary usage from 8-10 PM. From an application of solar water heating, this is a very favorable usage pattern, since the bulk of hot water is used soon after it is collected from the solar system.

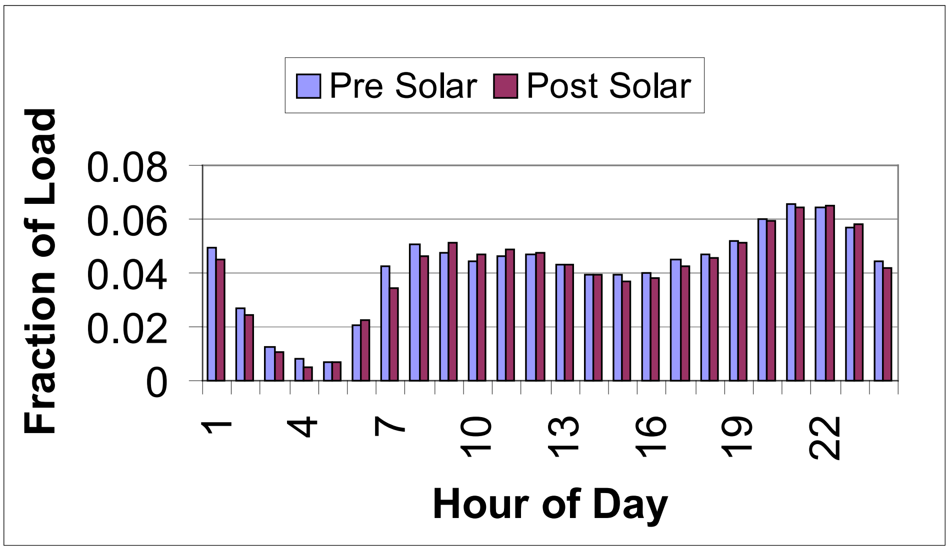


Figure 4.5-2. Annual Measured Water Usage Profile

Figure 4.5-3. indicates the variation in COP by site. One fact of interest is that the COP for the existing tanks is 0.73. Approximately 2/3 of these tanks were new with energy factors of 0.86 or higher. The Energy Factor is the COP under DOE (Federal Register 1990) test conditions of 135° F set point, 64.3 gallons/day, 58° F mains (inlet) temperature, and 67.5° F environmental temperature. Using Florida parameters, the COP would be slightly lower at 0.87. Because the measured values are lower than the required minimum energy factor, it is likely that site factors, including thermosiphoning in plumbing and non-ideal operating conditions (e.g. short draws), could result in a lower values. The post-solar COP does show sensitivity to region and system type. In general, the north (sites 8-14) has lower values than central (1-7 and 15-21), and the south (22-35) has the highest. Note that the southern values are highest for three reasons: warmer climate, active system type, and the use of on/off switches, which dramatically increase COP (in particular sites, 34 & 35).

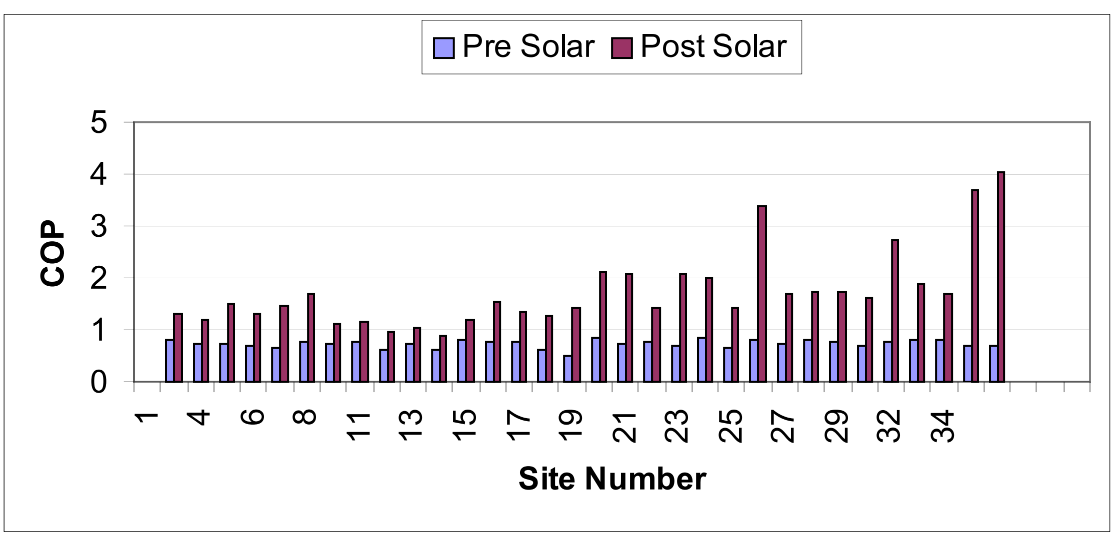


Figure 4.5-3. Pre- and Post-Solar Annual COP

Figure 4.5-4. indicates the pre- and post-energy usage for each site. One important thing to note is that low COPs do not necessarily imply low energy savings (the difference in pre- and post-solar usage). The pre-solar energy usage varies by site because of differences in water usage, set point, and existing water heater. Although these same factors also affect the post-solar energy use (and consequently the savings), other factors including the timing of load, radiation, and system performance are also important.

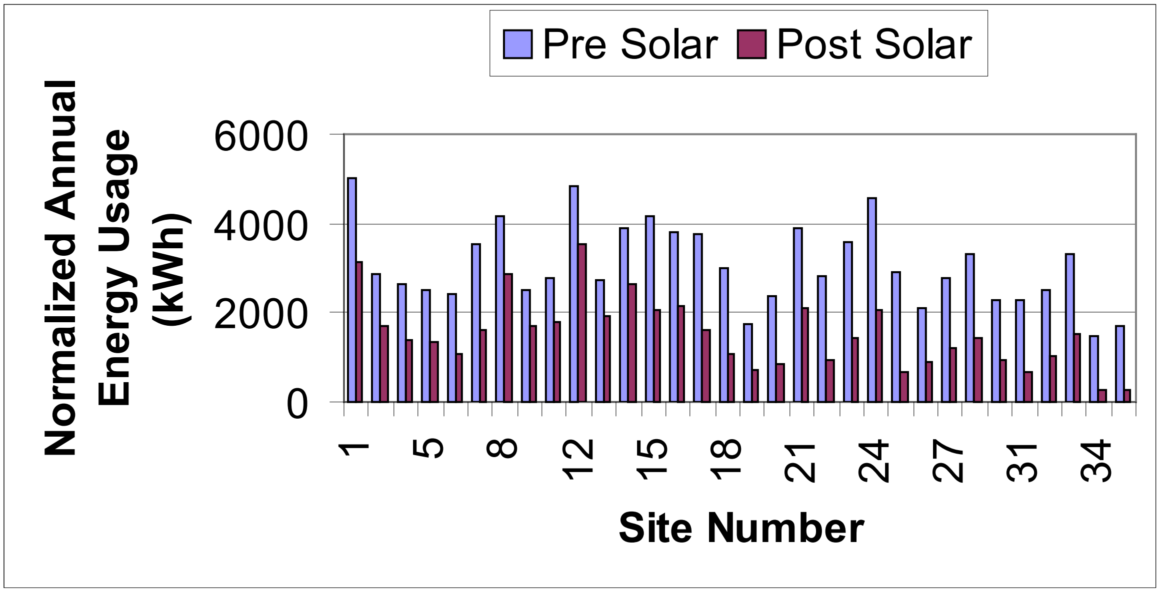


Figure 4.5-4. Pre- and Post -Solar Normalized Annual Energy Usage

One primary goal of this program is to evaluate the SIR of the systems. Figure 4.5-5. indicates the distribution of SIR's for monitored sites, given the assumptions for the SIR calculations. The break-even energy savings (SIR=1.0) is 1,540 kWh/yr (5.25 MBTU/yr) The average measured energy savings is 1600 kWh/yr (5.46 MBTU/yr). The distribution indicates that not all of the monitored systems have SIR's greater than 1.0.

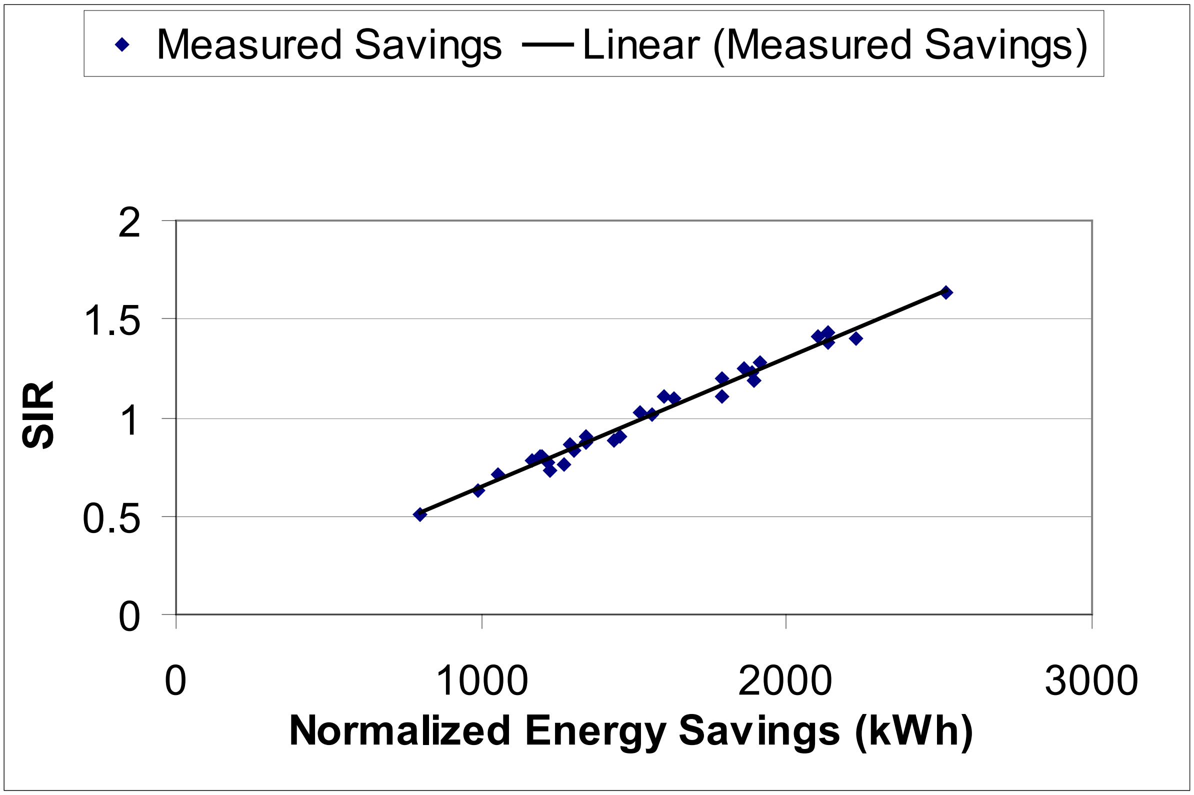


Figure 4.5-5. SIR vs. Normalized Energy Savings

A general summary of the hard monitoring is shown in Table 4.5-1. This table indicates that the two goals of an SIR of 1.0 and of a solar fraction of 0.50 have been met.

Table 4.5-1. General Hard Monitoring Summary

Parameter	Pre-Solar	Post-Solar
Average cold water temperature (° F)	76.7	76.7
Average hot water temperature (° F)	119.4	118.6
Average family size	4.6	4.4
Overall weighted COP	0.73	1.4
Flow/family-day (Gallons)	63.8	62.5
Flow/person-day (Gallons)	13.9	14.2
Average Installed System Cost ($)	N/A	1550
Average measured energy consumption (kWh /system)	3200	1500
Normalized solar fraction	0.0	0.53
Normalized SIR @ $0.08 /kWh	N/A	1.0
Normalized Energy Savings (kWh/year-system)	N/A	1600
Normalized Cost Savings ($/year)	N/A	130

Table 4.5-2 summarizes the individual data for each of the 32 monitored sites. This table is very important because it shows the direct comparison of one year's measured energy and usage data for hot water both before and after the installation of a solar system.

In the table, zone indicates the region of the state (N = north, C = central, S = south) where the system was installed. Type indicates the installed system type (ICS = Integral Collector Storage, A-DC= Active with differential control, and A-TC = Active with timer control). The number of occupants (# Ocp.) was figured as the average number of occupants during the time period. Average temperatures are based upon yearly averages. Flows are the flows delivered to the load (for post-solar, this includes the mixing valve effect). The pre and post energy usage is normalized to one year, but not normalized to average load. The post solar energy usage is broken down into the tank energy (Aux.) and the parasitic (Par.) energy (includes pumps, valves, and controllers for active systems). The Average COP is based upon the overall weighted energy usage (rather than an average of the COPs). The FEF (Florida Energy Factor) is calculated using a standard storage tank Energy Factor of 0.88 in place of the pre-solar COP. The summary values are normalized to the average delivered load. The important results of Table 4.5-2 are:

1. The pre-solar average COP of 0.73 is over 15% less than the standard Energy Factor of 0.88. Approximately 1/6 of the storage tanks were existing tanks.
2. The post-solar average COP of 1.43. The pre-solar COP for this system is implicitly included in this measurement.
3. The post-solar average FEF of 1.76. The standard tank Energy Factor of 0.88 was used for this calculation.

Determining why some sites saved more than others is useful for the future implementation of this type of program. In general, weatherization measures tend to best benefit the sites already using the most energy. This is illustrated for the SWAP sites by Figure 4.5-6. In this figure, the active systems show a better correlation than do the passive systems. Note that the straight-lines shown in Figures 4.5-6 and 4.5-7 are a best linear fit of the experimental data sets. The difference in the correlations is probably caused by two factors: the active systems offset some tank standby losses (and thus are easily correlated with the standby loss portion of the load), and the passive system performance is much more dependent on the profile of usage than are the active systems.

Figure 4.5-7 indicates that SIR does not correlate well with flow for either type of system. The passive fit is worse due to the reasons mentioned previously. Since the interest of this program is to ascertain which sites are best suited for solar weatherization, the sites were re-examined in term of factors that maximize energy savings. By examining the top performing systems (SIR>1.2), it is clear that high flow (given a relatively similar set of conditions and water heater set point) is critical to high savings, and thus high SIR. The average pre-and post flow for these systems (#15, #17, #21, #23, #24, #25, #28) is 80 gallons/day, which is approximately 30% higher than the mean for the group, although the reported occupancy (5) is approximately 10% higher than the mean for the group. Note that the pre-solar COP was identical to the whole group's value of 0.73, indicating that the pre-existing tank was not the significant factor in determining energy savings. Because there was significant scatter in the group, there is no clear cutoff for recommended sites; however, a pre-solar energy usage of 3,100 kWh/year (10.6 MBTU/year) or an average daily flow of 60 gallons/day or higher could be established as a minimum. As with other appliance specific weatherization measures, these values could be extrapolated from short-term monitoring of a given site and adjustment for seasonal usage.

The flow comparison also brings up another issue, the reliability of reported occupancy figures. The number of reported occupants in this group of 7 sites ranged from 3 to 9, indicating that flow, and thus energy savings is not ostensibly linked to occupancy. However, the variation in flow/ per person-day varied by a factor of 3, implying that the occupancy data may not have been too accurate, despite multiple attempts to get this information. Because of this factor, it is not clear that occupancy can be used as a means to select which sites receive this type of weatherization.

Table 4.5-2. Performance and Energy Summary by Site

			Pre Solar						**Post Solar**								**Summary** (Normalized)		
Site #	**Zone**	**Type**	**# Ocp.**	**Cold (F)**	**Hot (F)**	**Daily Flow (Gal.)**	**Aux. Usage (MBTU)**	**COP**	**# Ocp.**	**Cold (F)**	**Hot (F)**	**Daily Flow (Gal.)**	**Aux. Usage (MBTU)**	**Par. Usage (MBTU)**	**COP**	**FEF***	**Energy Saved (MBTU)**	**SIR**	**SF**
1	C	ICS	8	76.0	129.2	86.3	17.11	0.82	8	75.7	123.0	97	10.65	0.00	1.32	1.41	6.46	1.19	0.38
3	C	ICS	5.2	75.3	139.7	39.3	10.76	0.72	3	74.8	133.3	35.8	5.31	0.00	1.19	1.46	3.97	0.78	0.40
4	C	ICS	4	77.5	114.5	63.6	9.39	0.74	4	77.2	118.2	53.3	4.50	0.00	1.49	1.77	4.40	0.87	0.48
5	C	ICS	3	76.9	137.3	32.0	8.61	0.69	3	76.9	131.7	34.9	4.48	0.00	1.30	1.65	4.06	0.80	0.47
6	C	ICS	3	78.0	128.9	35.8	8.71	0.64	3	76.2	122.4	35.4	3.46	0.00	1.45	1.99	4.58	0.90	0.56
7	C	ICS	6	79.7	126.0	58.2	10.52	0.78	6	78.9	130.5	67.4	6.28	0.00	1.68	1.90	6.45	1.19	0.54
8	N	ICS	5	76.5	122.2	86.7	16.16	0.75	5	76.8	116.1	79.6	8.52	0.00	1.11	1.30	4.34	0.76	0.31
9	N	ICS	4	75.1	119.6	54.7	9.55	0.76	4	77.8	123.5	44.9	5.02	0.00	1.15	1.33	2.74	0.51	0.32
11	N	ICS	4	75.4	126.5	44.2	11.03	0.62	3.7	78.1	121.3	40.5	5.18	0.00	0.97	1.37	3.38	0.63	0.36
12	N	ICS	5	69.5	119.6	83.0	17.44	0.73	4	72.1	120.0	81.6	11.40	0.00	1.02	1.22	4.44	0.83	0.27
13	N	ICS	3	72.9	123.4	39.9	9.76	0.62	3	74.5	120.6	42.5	6.22	0.00	0.89	1.26	2.72	0.51	0.29
14	N	ICS	4	74.6	120.3	85.4	14.68	0.81	3.8	73.9	113.5	80.3	8.12	0.00	1.20	1.30	4.18	0.73	0.32
15	C	ICS	6	74.8	121.2	74.3	13.75	0.76	6	76.3	119.6	84.2	7.18	0.00	1.55	1.80	7.18	1.41	0.51
16	C	ICS	6	73.3	116.5	68.2	11.43	0.76	6	74.6	118.2	85.3	8.19	0.00	1.35	1.56	5.57	1.10	0.43
17	C	ICS	3.5	71.9	115.3	55.0	12.08	0.60	3.2	74.8	122.0	56.7	5.83	0.00	1.26	1.85	7.30	1.44	0.57
18	C	ICS	3	75.1	132.1	29.1	9.60	0.51	3	76.3	124.7	37.6	3.79	0.00	1.43	2.46	6.53	1.28	0.64
19	C	ICS	4	74.3	117.8	39.0	6.10	0.84	4	76.1	119.3	38.5	2.41	0.00	2.13	2.24	3.59	0.71	0.60
20	C	ICS	5.3	76.2	111.7	58.7	8.59	0.75	3	75.6	116.5	44.1	2.66	0.00	2.07	2.43	5.19	1.02	0.64
21	C	ICS	5	76.6	117.3	82.3	13.30	0.76	5	77.1	118.2	80.7	7.11	0.00	1.42	1.65	6.10	1.20	0.46
22	S	A-DC	4	79.4	113.9	64.9	9.38	0.71	5	79.9	112.0	78.3	2.71	0.62	2.06	2.44	6.43	1.22	0.66
23	S	A-DC	3	78.4	116.3	96.7	13.16	0.83	3	78.7	114.6	94	4.11	0.40	2.00	2.11	7.28	1.39	0.6
24	S	A-DC	9	79.5	118.2	100.8	17.67	0.66	9	79.9	120.0	82.8	5.72	0.30	1.43	1.87	8.60	1.64	0.55
25	S	A-DC	5	79.0	116.8	78.4	11.17	0.80	4.2	78.8	108.9	79	1.58	0.45	3.37	3.62	7.59	1.40	0.77
26	S	A-TC	4	77.3	111.9	42.5	6.16	0.73	4	76.5	115.9	53.8	3.18	0.32	1.68	1.99	4.09	0.80	0.57
27	S	A-DC	4	79.9	113.0	76.2	9.57	0.80	3.5	80.4	112.3	79.8	3.75	0.32	1.73	1.89	5.31	1.01	0.56
28	S	A-DC	4	78.5	111.6	98.2	13.09	0.76	3.5	77.1	109.0	76.2	3.83	0.35	1.73	1.98	6.36	1.25	0.56
29	S	A-DC	4	79.8	118.7	50.2	8.75	0.68	4	78.4	120.5	40.3	2.17	0.61	1.62	1.96	4.60	0.87	0.59
31	S	A-TC	5	78.2	103.8	87.3	8.26	0.76	5	78.6	108.8	65.2	1.73	0.33	2.75	3.10	5.46	1.11	0.71
32	S	A-DC	4	80.5	115.2	74.6	9.63	0.81	4	78.9	112.2	63.4	2.74	0.41	1.90	2.04	4.97	0.90	0.58
33	S	A-DC	5	79.7	115.8	81.9	10.99	0.80	5	81.8	113.0	106	4.93	0.32	1.71	1.87	6.11	1.11	0.54
34	S	A-TC	4	77.5	110.4	37.5	5.63	0.68	4	76.6	114.5	26.6	0.43	0.33	3.71	4.27	4.16	0.77	0.82
35	S	A-DC	6	77.2	117.5	35.2	6.17	0.71	6	77.8	120.8	34.7	0.58	0.35	4.04	4.57	4.89	0.89	0.83
Avg. / Sum			**4.6**	**76.7**	**119.4**	**63.8**	**348.23**	**0.73**	**4.4**	**77.1**	**118.6**	**62.5**	**153.77**	**5.12**	**1.43**	**1.76**	**169.02**	**1.0**	**0.53**

* FEF= Measured Florida Energy Factor calculated using a standard Energy Factor of 0.88 for auxiliary energy usage.

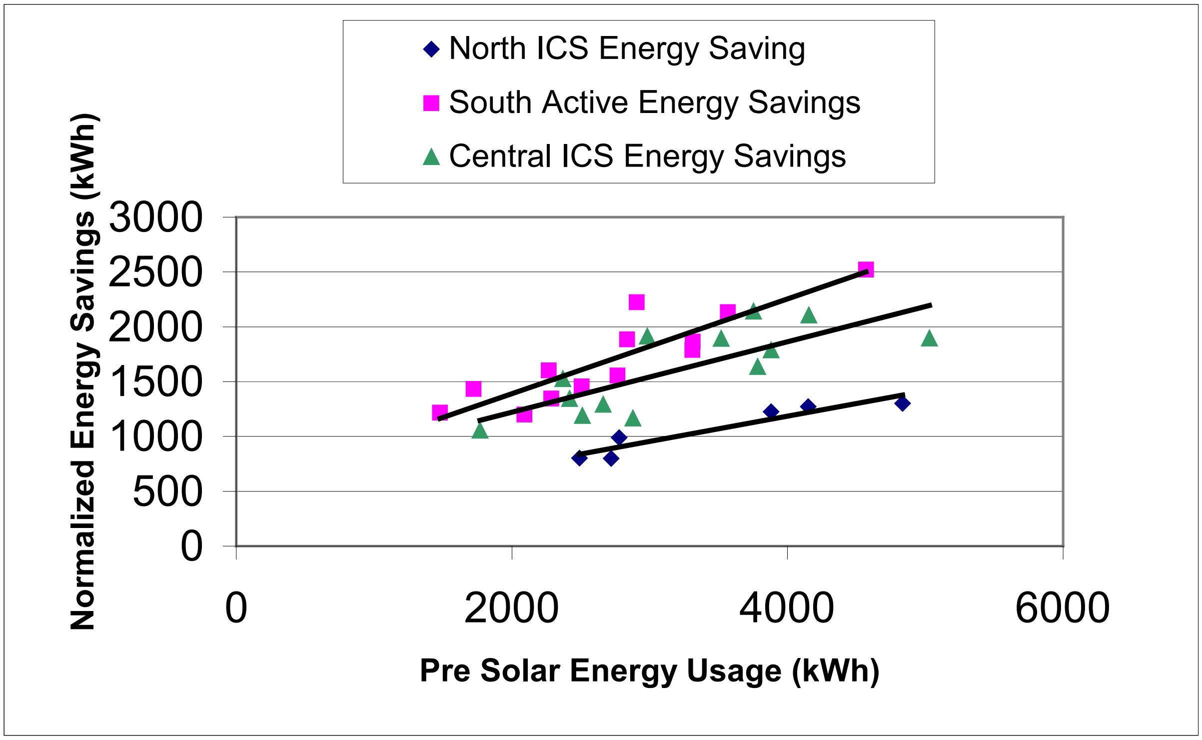


Figure 4.5-6. Energy Savings vs. Pre-Solar Energy Usage

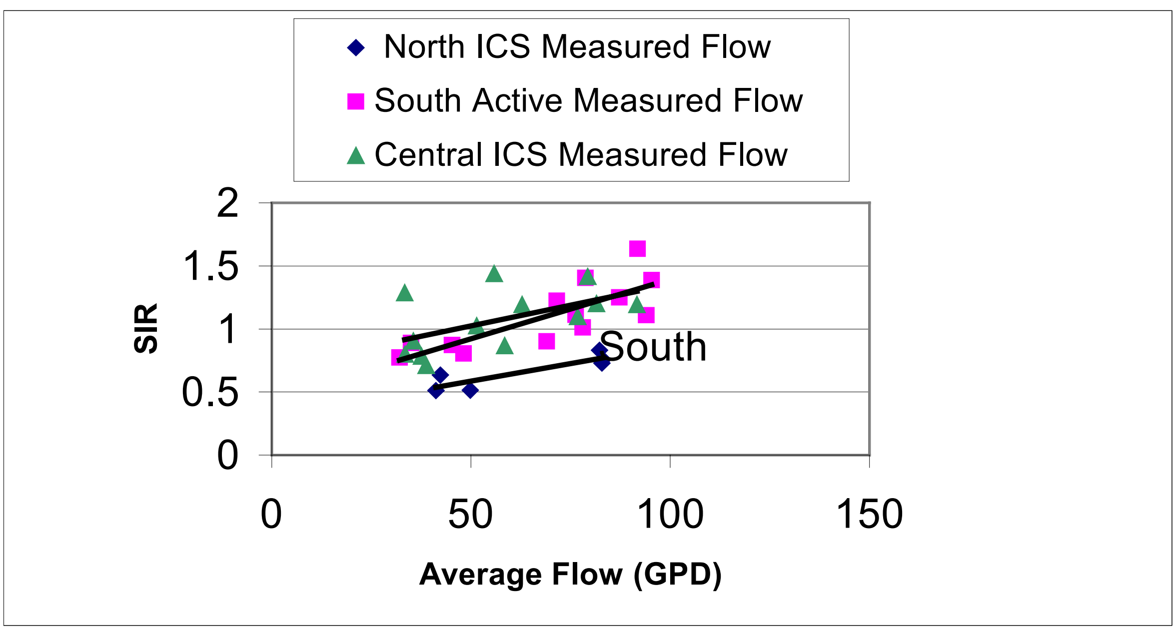


Figure 4.5-7. SIR vs. Flow

4.6 HARD MONITORING: COMPARISON WITH F-CHART PREDICTIONS

As part of the data analysis for the SWAP program, a comparison between the measured data and the predicted results from F-Chart (F-Chart 1993) simulation program was undertaken. There are several reasons for this comparison:

1. If the SWAP program is accepted as a standard weatherization option, F-Chart is one means by which solar system savings could be quantified in different climatic regions.
2. F-Chart is the basis for which Energy Factors for Florida are calculated.
3. The SWAP data provide a good basis for further validation of the F-Chart program.

F-Chart has been previously documented to reproduce experimental data to within 5% for active systems in the laboratory (Fanney and Klein, 1983) and to within 11% for systems from the National Solar Data Network (Duffie and Mitchell, 1983). An interest to the SWAP program is if F-Chart can predict field results to within +/-10% using field level (e.g., site and non-site measured meteorological) data.

In order to make a meaningful comparison between the measured and predicted values, it is necessary to obtain as much detailed information for all parameters as is possible. Because F-Chart uses monthly calculations, the monthly data for each of the selected sites are used. Several of the hard monitoring sites (#14, #15, #17, #19, #21, #24, #26, and # 31) were not used because large gaps (in excess of 1 month) existed in the data. This would have made F-Chart comparisons difficult to assess because F-Chart works with monthly intervals for one year.

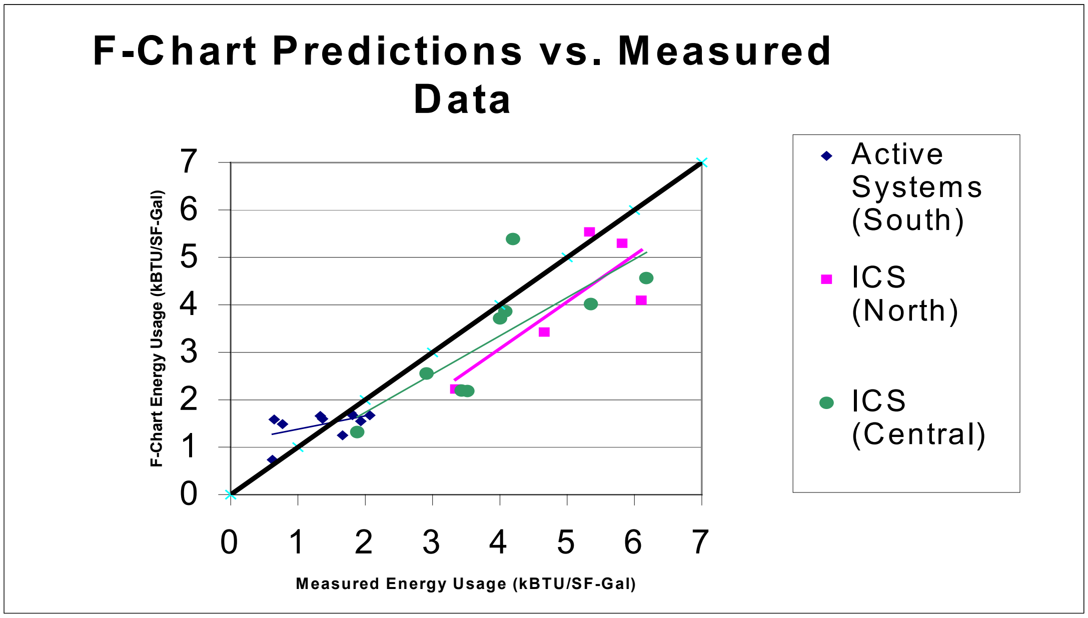
The data to drive the F-Chart program were entered from the monthly performance summaries, ambient temperatures from the adjacent meteorological stations, and system data from the inspections. Because the driving data for F-Chart is identical to that measured at the actual sites, this method should give an idea about how well F-Chart models the measured data. For ease of comparison, the month nearest the installation/completion dates were used as a basis for the comparison. In cases where this was not feasible, the site was dropped (sites #14, #15, #19, #24) from the comparison.

In doing the comparison, there is one piece of data that was not explicitly measured: the tank UA value. The UA value expresses the total amount of standby loss that the tank will have as a function of the temperature difference between the tank and its surroundings. The nominal value could be used, but this value is not typically the value experienced in actual installations (it may vary by a factor of 2). The pre-solar data were used to calculate the UA value for the F-Chart simulation. For the pre-solar phase, and the UA calculations, measured environmental temperatures were used. Because this information was not measured in the post-solar phase, it was assumed that the pre-solar and post-solar environmental temperatures were the same. This is one potential source of error, although the magnitude of error is probably not more than 3% of the total energy usage. For the post-solar phase, the pre-solar UA value was used as the basis of the calculations.

Table 4.6-1 indicates the comparison of predicted and measured energy usage for the selected sites. This data indicates two primary things:

1. The calculated energy usage compared to the measured usage for the ICS sites (#1-21) is under predicted in all but two cases (#11 & #18). F-Chart under predicts ICS energy usage by 19% for the group.

2. F-Chart over predicts the energy usage by 5% for the active systems group. For the active systems (sites #22-35) there is no clear trend: some cases are high and others are low. Note that the comparison for the active systems does not include parasitic energy usage.


F-Chart Predictions vs. Measured Data
F-Chart Energy Usage (kBTU/SF-Gal)
Measured Energy Usage (kBTU/SF-Gal)
0
1
2
3
4
5
6
7
Active Systems (South)
ICS (North)
ICS (Central)