THE EFFECTS OF SOLAR WATER HEATING ON WINTER PEAK ELECTRICAL DEMAND

By

BENJAMIN SPENCER SWANSON

A THESIS PRESENTED TO THE GRADUATE SCHOOL
OF THE UNIVERSITY OF FLORIDA IN PARTIAL FULFILLMENT
OF THE REQUIREMENTS FOR THE DEGREE OF
MASTER OF SCIENCE

UNIVERSITY OF FLORIDA

2013

To my mom. You have no idea.

ACKNOWLEDGMENTS

I would like to take this opportunity to express my gratitude to my committee, Dr. William Lear and Dr. Herbert Ingley for their guidance, support, and patience during this season of life and the thesis that has come of it. I owe my deepest thanks to Dr. James Fletcher for his relentless encouragement to finish strong and for the many hours of support during the research and writing. I would also like to thank Dr. Neal Coulter and Dr. Joseph Campbell for their wisdom and encouragement. I thank Beaches Energy, APPA, and JEA for funding, cost share, and oversight. Finally, I thank Jason Harrington for long hours of help and friendship during classes, homework, research, thesis and the distracting conversations that make up life.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF ABBREVIATIONS

APPA	American Public Power Association
ASES	American Solar Energy Society
ASHRAE	American Society of Heating, Refrigeration and Air-Conditioning Engineers
BA	Building America
DEED	Demonstration of Energy & Efficiency Development
EPDM	Ethylene Propylene Diene Monomer
FPL	Florida Power and Light
FSEC	Florida Solar Energy Center
ICS	Integral Collector Storage
KAU	Kissimmee Utility Authority
LOLP	Loss of Load Probability
NREL	National Renewable Energy Lab
OPEC	Organization of Petroleum Exporting Countries
P&ID	Piping and Instrumentation Diagram
SRCC	Solar Rating Certification Corporation
TMY2	Typical Meteorological Year data set 2
TRNSYS	Transient System Simulation Tool
USA	United States of America
USD	United States Dollar
VAC	Voltage Alternating Current
VDC	Voltage Direct Current

Abstract of Thesis Presented to the Graduate School
of the University of Florida in Partial Fulfillment of the
Requirements for the Degree of Master of Science

THE EFFECTS OF SOLAR WATER HEATING ON WINTER PEAK ELECTRICAL DEMAND

By

Benjamin Spencer Swanson

December 2013

Chair: William E. Lear, Jr.
Major: Mechanical Engineering

Solar water heaters have demonstrated the ability to use the sun's energy to produce hot water, thus displacing the need to use electricity and the resulting fuel usage, cost, emissions, etc. Many utilities have begun to investigate whether other benefits can be gained from solar water heaters. Most utilities in the Southeast of the United States experience peak demand for electricity during the winter months due to high electrical demand on cold mornings for space heating and hot water usage. This investigation, funded and supported by APPA, JEA, and Beaches Energy, studies the potential for solar water heaters to reduce winter electrical peaks.

An integrated ICS solar/electric water heating system was installed at Beaches Energy Services in Jacksonville Beach, FL. The system was fully-instrumented and controlled to mimic typical hot water usage for a family of two. Data was collected over a two-year period, with focus on winter months. Testing showed that on the coldest winter mornings, the hot water demand averaged 14.4 kWh, with the solar hot water contributing 6.4 kWh or 44%. Comparison of experimental data to NREL's solar heating model built on a TRNSYS platform showed similar trends with the major difference being lower transmissivity of the experimental solar collector as compared to the model

default values due to dirt and salt associated with the beaches environment. The experimental data showed that a properly installed and maintained integrated solar/electric hot water system has the potential, on cold winter mornings, to reduce electricity usage by more than 40%.

CHAPTER 1
INTRODUCTION

Solar Water Heating

Solar water heaters have demonstrated the ability to use the sun's energy to produce hot water, thus displacing the need to use electricity and the resulting fuel usage, cost, emissions, etc. Many utilities, especially those in the Southeast of the United States, have recognized the advantages of solar thermal technology and established incentive programs to facilitate wide-spread use. Despite the many benefits of solar water heating, the utilities are in a sense subsidizing the customer to not use the utility company's product, i.e. electricity. As a result, the utilities have begun to investigate whether other benefits can be gained from solar water heaters.

Many utilities in the Southeast of the United States, such as JEA in Jacksonville, Florida, experience peak demand for electricity during the winter months [1]. This is due to many customers using electricity for space heating and hot water usage, both of which undergo high demand during cold winter mornings [2]. Minimizing peak electrical demand, given that electricity is generated with regard to demand because it does not lend well to storage, is critical for utilities to avoid brown-outs as well as to avoid the requirement to build new power plants, a costly endeavor [3]. There exists the possibility that solar water heating technology, properly designed and implemented, could provide thermal hot water capacitance/storage and thus reduce the need for electricity during this critical period and provide a quantifiable benefit to the utility [4].

Water Heating

Domestic water heating accounts for a significant fraction of Florida's residential electrical consumption, with studies showing ranges from 13% to 21% [5]. During the winter peak demand, the fraction of electrical consumption increases to 25% [6]. Currently, electric resistance water heaters are responsible for 99% of the electricity consumed heating water for residential dwellings in Florida [6], thus there exists a large opportunity to reduce the winter peak load by implementing solar water heating technology [6]. The benefits also extend to the customer, given that research has shown that solar water heating has the potential to meet 90% of the residential hot water needs [4].

The solar water heating systems installed in the United States as of 2010 provide enough hot water for 1.5 million homes [7]. In 2010 alone, over 35,000 solar water heating systems were installed which represents a 6% increase from 2009 [8].

Solar Water Heating Design

Solar water heating systems consist of a solar collector, a storage tank and depending on the technology, a pump that runs on electricity [9]. A solar collector is a heat exchanger that absorbs the incoming solar irradiation and transfers that heat to water flowing inside the tubes. Unlike typical heat exchangers that transfer heat from one fluid to another, solar collectors depend on radiation from the sun for input energy. The incident radiation varies with sun position and cloud cover, but can provide flux levels up to 1100 W/m^2 [10] or if sustained for an hour up to 66 kWh /m^2.

Systems typically fall into either an active or passive design category. The active designs use pumps and controllers to circulate fluid between the collector and a heat exchanger or collection tank. Due to the ability to circulate water even during times of low or no hot water usage, heat can be transferred to the water storage tanks more efficiently. Active systems provide the advantages of higher efficiency and better protection from freezing, but suffer the disadvantages of higher initial costs and the loss of functionality during power outages.

Passive systems, which have no moving parts or electrical demand, circulate water through a collector by relying on the pressure from the water supply. The system is typically plumbed in series with a standard water heating tank. Passive systems have no electrical components to fail which can provide greater reliability, but are more susceptible to freezing if located in regions with extreme weather [9].

A common passive system that is often part of utility incentive programs is the integral collector storage system (ICS). An ICS system is made up of interconnected tanks coated with high absorption paint enclosed in an insulated structure. The top of the structure has a transparent cover to admit radiation from the sun. Throughout the day, the water inside the tanks absorbs the solar energy raising the temperature of the water [10]. Figure 1-1 [11] illustrates the basic principles of ICS solar collection.

An ICS system serves to preheat the water going into a conventional domestic water heater and provide supplemental storage. ICS systems are very popular due to their simplicity and historically lower costs. Because the supplemental storage is located inside the unit, ICS systems are not as well protected from freezing as some of the other systems. Fortunately, in more mild climate regions such as the southeast, long and frequent freezes are rare and typically do not last long enough to freeze the large volume of heated water within the integrated collector.

ICS Background

The first ICS systems were constructed in the late 1800s. The water storage took place in four galvanized iron cylinders contained in a five sided wooden box. The cylinders were painted with a dull black paint to maximize heat absorption and the box was lined with felt paper for insulation. Instead of an open top, a single-glazed aperture was installed to insulate the box and increase efficiency. In 1892, the units marketed under the name Climax Solar-Water Heater were sold for 15 USD and over a 5 year period 1600 units were sold in the state of California. The early inventors and entrepreneurs did very little systematic studies to increase performance, but in 1936 the first detailed study was conducted at the University of California Agricultural Experimental Station. The performance differences between exposed and closed boxes were investigated, as well as using single ICS tanks versus multiple tanks. Just as interest in optimization began to gain traction, the discovery of oil fields and natural gas coupled with promotion and subsidies for these fuels brought solar research to a halt in the United States until the early 1970s [11].

In Japan, however, development was stimulated due to a lack of fossil fuels and the resulting high-energy costs. Commercial units in Japan came to market in 1947 and in the late 1950s the ‘closed-pipe’ ICS system constructed of stainless steel was released. During the same time period an ICS system using a polyvinylchloride bag was developed. This style was nicknamed the ‘plastic pillow’ because of the design of the closed membrane. With a peak of 240,000 units sold in the production year 1963-1964, the ‘plastic pillow’ had great commercial success. In response to the OPEC-embargoed Arabian oil in the early 1970s there was resurgence in solar energy as a viable source for water heating in the USA, South Africa, Australia and Japan. With this renewed interest, universities, research institutions and solar enthusiasts began putting effort and resources into furthering ICS systems as an alternative to the conventional domestic water heaters of the era [11].

The popularity of ICS systems from inception has always been closely tied to the availability and cost of energy. In principle, the ICS design has not changed a great deal since the first units produced over a century ago. The early systems lost a great deal of heat to the ambient during long periods of little to no collection and during the night. This is still a concern today.

Solar Water Heating Incentives and Rebates

Many utility companies, including JEA and Beaches Energy in Jacksonville, Florida, have long running programs of financial incentives to encourage the installation and use of domestic solar water heating. JEA provides $800 per residential installation and gives 30% of the total up to $5000 toward commercial systems [12]. Beaches Energy, of Jacksonville Beach has a $500 rebate for residential solar water heating installations [13]. Of the solar water heaters installed from JEA's incentive program a significant fraction have been ICS systems [5].

Peak Electrical Demand

Peak Demand Risks

Peak electrical demand is an important issue for utility companies. During times of low demand, utility companies are able to maximize efficiency by operating the lowest marginal cost plants. During periods of near peak demand, the utility companies bring online all of their available electricity producing units to prevent outages. Loss of load probability (LOLP) is a way of quantifying risk for utility groups and is greatest at peak times. Economic efficiency, environmental quality, fuel security and facility siting are all factors that are detrimentally impacted by operating near the margins of maximum output. Typical load shifting strategies require smart controls to shift a percentage of the energy use to off peak times or to attempt to store energy during low demand for times of higher demand [14]. Solar water heating, due to its energy capacitance, has the potential to store surplus energy collected the afternoon before for use during the peak and act as a load shifting option.

Winter Peaking

The southeast, with much milder winters than the majority of the United States, seems like an unlikely region for winter peaking. During the hot summers, the overall electrical loading is high, but the loading is not as concentrated as on cold winter mornings. This is, in part, a result of heavy dependence on electrical resistance space heating versus dependence on wood, heating oil, and natural gas fuels that are used in many of the colder winter regions. On January 11, 2010 at 7:10 AM, JEA set a new record for peak electrical demand [1]; similarly at 7:04 AM the same day, Kissimmee Utility Authority (KAU) experienced a new record [15]. Even in Atlanta, Georgia, during the same day between 7 AM and 8 AM, the Southern Company set a new record [16]. Florida Power and Light (FPL) had 14,000 homes lose power by midmorning on January 11, which FPL attributes to the added power consumption related to space heaters and inefficient home heating systems [2].

Solar Water Heating as a Reduction Method

The potential for solar hot water heaters to provide peak demand reduction for winter peak utilities has not been extensively researched in the published literature. One publication, “Utility Success Stories in Solar Water Heating,” published by the American Solar Energy Society (ASES), detailed that Lakeland Electric saw a reduction of 0.7 kW per system during their winter peak when used in conjunction with a 7 AM - 7 PM timer that interrupted the electric supply [4]. The type of systems and installation requirements, however, were not detailed. Most of the published literature in this area does not provide detailed accounts of how peak savings were achieved. For solar water heating to effectively reduce winter peaking, the heat energy gained during the day must be maintained through the cold night and available for use during the morning activities of the residential customers, namely showering and kitchen needs. The concern is whether the heat energy gained by solar radiation during the day would be lost via radiation and convection during the cold winter nights, potentially requiring the electric hot water heaters to consume the same if not more electrical energy.

This Study

In this thesis, the potential for solar water heaters, specifically of the ICS design, to reduce winter electrical peaks is studied. The study includes an ICS system integrated with an electric water heater with appropriate controls and instrumentation to simulate typical residential water usage and monitor the effects. The collected data was compared to an NREL [17] model built off of a TRNSYS platform to project monthly performance and the effects on energy use. The experimental data and the modeled results were used to evaluate the potential peak load reduction on winter mornings through implementation of a solar water heating ICS system.

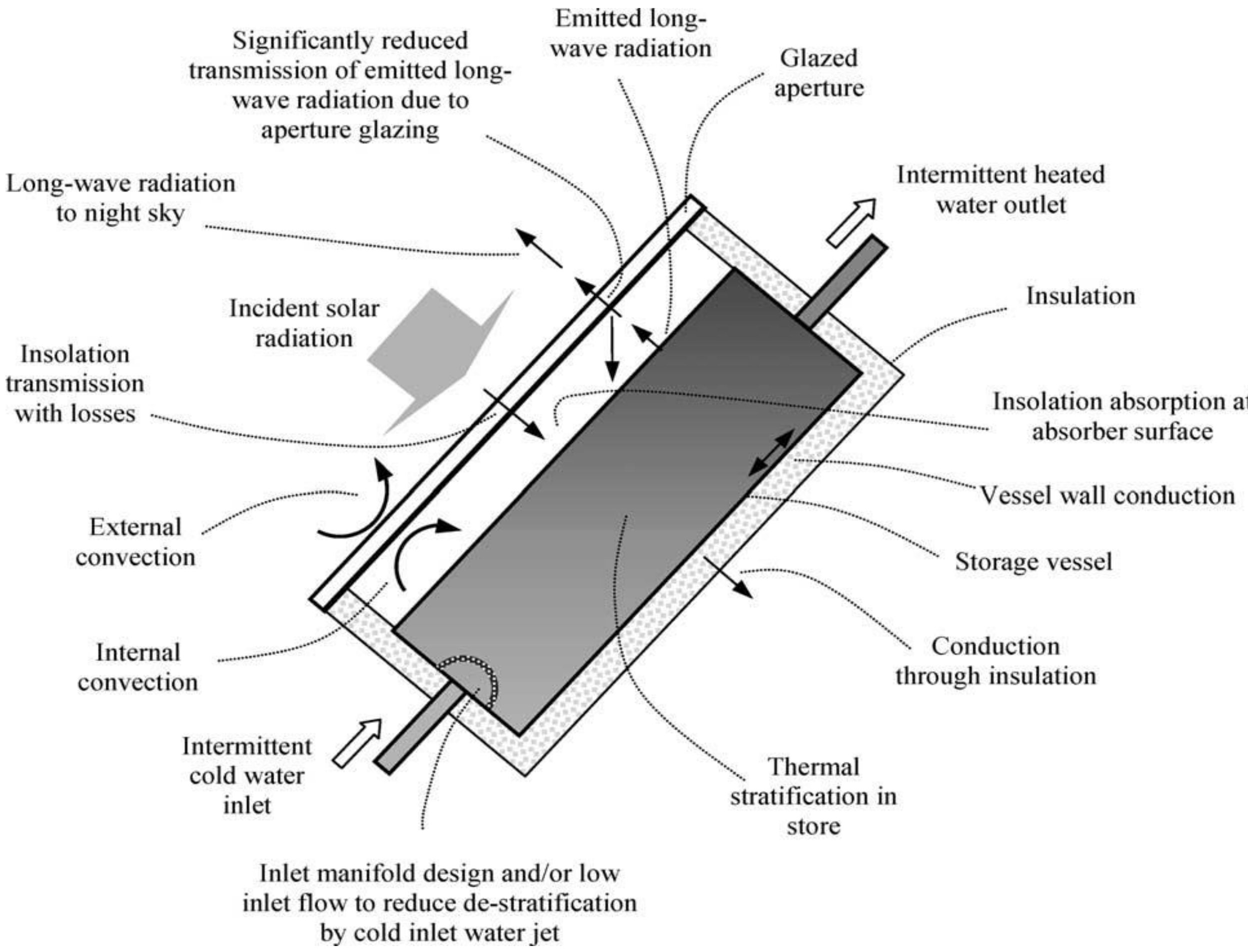

Figure 1-1. ICS solar collection basic principles. [11] (Source: M. Smyth, P.C. Eames, B. Norton, Renewable and Sustainable Energy Reviews, (2004))

CHAPTER 2
LITERATURE REVIEW

This chapter presents a review of literature on solar collector performance, residential electricity and hot water consumption, solar modeling, solar experiments and peak reduction.

Solar Collector Performance

Published literature includes studies that indicate implementation of solar water heating technology can reduce the overall energy use in typical households. Kettles and Merrigan [18] found over 2500 publications related to solar water heating performance. A selection of representative studies were reviewed and summarized. The studies were grouped into two time frames; late 1970s and early 1980s. The reporting shows an average savings of 1830 kWh/year from the early time frame. Specific to Florida, studies done by the Florida Solar Energy Center between 1978 and 1980 revealed an energy savings of 2232 kWh/year. The findings from the later time frame were an average of 2502 kWh/year savings nationally and the Florida Public Service Commission's findings were 2044 kWh/year of savings between 1982 and 1984 locally. The average electric water heater in Florida uses approximately 3000 kWh/year. This reporting suggests that solar energy has the potential to displace between 68% and 74% of the electrical energy required to meet the water heating needs of the average household.

Masiello et al. [19] published a study based on 171 residences in central Florida revealing domestic hot water used 2240 kWh of the 17,130 kWh total for the average annual electrical load of a household, approximately 13% of the total. Four residences that included solar water heating exhibited a 61% reduction.

Moore [5] estimates that solar water heating decreases the typical household energy use by 8%-10% based on a correspondence with Danny Parker from the Florida Solar Energy Center.

Merrigan and Parker [6] monitored eighty single family residences for two years in Florida. Twenty of the homes used solar hot water systems and averaged 2.7 kWh per day versus the 8.3 kWh used by the electrical resistance water heaters.

Parker [20] found solar to provide a 61% reduction against conventional electric water heating in a study of 204 residences in central Florida. Of the 204 residences, 150 were electric resistance and 4 were solar.

Progress Energy Florida (formerly Florida Power Corporation) estimates that incorporating a solar hot water heater reduces the daily energy use associated with hot water from 7.69 kWh to 3.11 kWh [5].

Solar Collector Modeling

TRNSYS was originally developed in 1973 at the University of Wisconsin Solar Energy Laboratory. From conception, the purpose of TRNSYS was to simulate thermal energy systems making it an invaluable resource for solar and other renewable energy source modeling [10]. Commercially TRNSYS is used by the Solar Rating Certification Corporation (SRCC). The SRCC is designated by the U.S. Government to validate the performance of solar energy sources for the purpose of federal tax credit eligibility [21].

Haberl and Cho [22] reviewed a collection of publications to determine the uncertainty of different approaches to solar modeling. The findings revealed TRNSYS simulations often agreed within 5% of the experimental results.

Solar Collector Experimental Setup

This section reviews the different experimental arrangements used in the published literature to evaluate the performance of typical solar hot water systems.

Colon and Parker [23] conducted a solar water heating performance study for the U.S. Department of Energy on site at the Hot Water System Laboratory at the Florida Solar Energy Center in Cocoa, FL. To model a typical household, a 32 square feet ICS system was installed facing due south with a pitch of 22° from horizontal. The solar panel was installed preheating the water inlet to a standard 50-gallon water heater. The ICS system used in the test is a PT40-CN (Thermal Conversion Technologies) Progressive Tube Collector with 32 square feet of surface area and 40 gallons of internal storage. Temperatures were measured and collected at the tank inlet and outlet, mixing valve outlet and the mains inlet. Flow measurements were taken to quantify the total number of gallons going through the collector and used for mixing. Electrical energy was measured to quantify the frequency and usage of the resistive tank elements. The water was drawn at 1.5 gallons per minute according to the water draw profile. The water draw profile is further explained in the Hot Water Use section.

The Solar Rating & Certification Corporation (SRCC) [24] has done extensive performance and durability testing on solar collectors and systems. The collectors are positioned and fixed at 0° azimuth (due south) and normal to the sun at solar noon +/- 4°, unless this contradicts the manufacturer's installation instructions for tilt. Instrumentation is installed to measure inlet and outlet temperatures, ambient and environmental temperatures, fluid flow rate, wind velocity, auxiliary energy use when applicable, and radiation data. Other information necessary for the performance testing and reporting is the fluid heat capacity, particularly in cases where potable water is not the heat transfer fluid, the local and solar time, and date and year of the testing.

Hot Water Use

This section reviews the published literature concerning modeling the quantity of hot water use and typical hot water draw throughout the day. Many of the papers reviewed are focused on the Southeast region, Florida in particular.

Parker et al. [25] published a study on the energy use patterns and determined the average dwelling to have 4.6 occupants. On average, 63.6 gallons of domestic water heating were required to meet the needs of the average household. The lowest hot water consumption falls between the hours of 11:01 PM and 6:00 AM. The highest usage is between 6:01 AM and 8:00 AM and is about 4.5 gallons per hour.

Lutz et al. [26] determined that the average household in Florida is made up of 4 occupants and uses between 64.7 and 74.6 gallons of hot water. The study showed that households with electric water heaters use less hot water than households with gas water heaters. This is a result of the behavior patterns of the occupants shifting to avoid running out of hot water because of the slower recovery rates of the electric water heater.

Parker [20] observed Florida’s tendency to have surprisingly intense winter electrical demand peaks as a result of the severe, but infrequent cold snaps. Combatting the peak loading is difficult due to the electrical demand for the majority of the year does not requiring additional generation capacitance. As a result of this observation, the study monitored 150 conventional electric resistance water heating units with storage tanks and four solar water heating systems. Of those monitored, 80% of the water heaters were located in unconditioned space. The average number of occupants was 2.81 with the most common being 2. The temperature of the water from the tap ranged from 19.4°C in February to 27.2°C in September. The average mains temp was 24°C. A 15-20% increase in hot water use during the winter season as compared to the summer was observed. The conclusions drawn from this increase are that more hot water is needed for mixing as a result of the lower mains temperature and residents take longer showers when the average air temperatures are lower.

In a study by Colon and Parker [23], the water draw profiles used to mimic family use were alternated between the ASHRAE 90.2 with a set draw of 64.3 gallons per day and a dynamic draw profile based on a study of water usage conducted by Building America (BA) and the National Renewable Energy Lab (NREL) with an average of 54.8 gallons per day. Though the dynamic draw patterns of NREL/BA vary from month to month, the January pull is 67.2 and the February and March pulls are 66.4 gallons per day which are very similar to the ASHRAE 90.2 draw profile.

The Solar Rating & Certification Corporation [27] has an approximate volume draw of 64.3 gallons per day at a water temperature of 14.4°C. The water is drawn at three gallons per minute at six different consecutive hours starting at 9:30 AM.

Electrical Use

Moore [5] claims the greatest domestic energy use, after HVAC, is attributed to water heating, ranging from 13% to 21%.

Parker et al. [25] published test results from FSEC showing that hot water heating requirement accounts for 8.0 kWh of the total 42.8 kWh consumed for the day, which calculates to 18.7%. Lutz et al. [26] determined residential water heaters make up 11% of electricity consumed in the average household.

Parker [20] included monitoring 204 residences in Central Florida. The total average annual electricity load was 17,130 kWh of which 2,240 kWh was from water heating. This calculates approximately 13% of the total for domestic water heating.

Merrigan and Parker [6] monitored eight single family residences for two years in Florida. Electric water heaters averaged 8.3 kWh per day of electrical consumption and had an average system efficiency of 82%. The residences that implemented solar water heating systems averaged only 2.7 kWh per day, a reduction of 5.6 kWh.

Colon and Parker's [23] research revealed the inlet feed from the water mains varied by close to 19°C from the coldest to the warmest months of the test. The low was 10.6°C and was experienced in December. This number has a great effect on the performance of the solar water heating system and also on the amount of hot water used for mixing to get the appropriate temperature for usage. During the warmest month, about 4.15 kWh is required to bring 50 gallons of water at mains temperature up to the 49°C set by the mixing valve. During the coldest month, about 8.4 kWh is required to do the same. This translates to twice the energy required to get the same volume of 49°C water delivered to the consumer. The testing of an ICS system shows an average temperature outlet of about 27°C during the coldest winter months. Based on the average outlet temperature, the test suggests the ICS system is capable of compensating for the difference in the mains temperature. There is a 63% variance in daily energy use for water heating from January to July. A closer look at the monthly performance in the winter resulted in 7.96 kWh/day for the ICS feeding a 50 gallon electric heater compared to 8.51 for a standard electric tank in December 2009, 9.29 vs. 10.52 in January 2010 and 9.39 vs. 10.41 in February 2010 respectively. The annual difference resulted in 1703 kWh vs. 2692 kWh. The difference in the winter month savings appear to be small, but when summed on an annual basis become substantial.

Peak Reduction

Lutz et al. [26] concluded that due to the thermal storage capacity of water heaters, they are ideal for load management strategies. The load management strategies utilizing solar water heating includes “valley-filling” of daily electrical load profiles and also “peak-shaving”.

Merrigan and Parker’s [6] published literature states that approximately 50% of all electricity consumed of the total annual use in Florida is residential and 21% of that is water heating. Only 1% of the water heating technologies in use in Florida are from alternative sources. Consumption of hot water in the winter increased from summer on average by 27% and the electricity demand increased by 47% to make up the difference for the increased demand and the extra electricity required to heat the water as a result of lower inlet water temperatures. This translates to electric resistance water heaters being responsibly for approximately 1.1 kW of the 4.2 kW that each residential customer contributes to the winter peak. Of that, customers using solar water heating experienced a 0.7 kW reduction. This reduction has the potential for a substantial shift in the demand profile relative to coincident peaks experienced in Florida.

Parker’s [20] residential monitoring study included four houses with solar water heaters. The houses with solar water heating systems saw a 61% annual energy reduction compared to the houses with conventional electric units, or 1,420 kWh/year. The peak reduction was 0.31 kW for the winter and 0.14 kW for the summer.

Colon and Parker’s [23] data reveals the ICS system saved close to 2.5 kWh/day. Looking at the potential for morning peak demand reduction, the data at 8:00

AM was analyzed and the ICS-50 system provided a 14% reduction on average. A 35% reduction was experienced on average during the entire morning peak time window. A 50% evening peak reduction was experienced using the ICS. A closer look at the effects on winter peak demand show conflicting evidence. The paragraph states that a 30% reduction was experienced during the highest average peak demand which occurred at 8:00 AM in February 2010, but the graph in the literature demonstrates the ICS coupled to the 50 gallon electric tank used greater than 10% more electricity than the 50 gallon benchmark system. The daily percent reduction for the ICS using the ASHRAE 90.2 draw profile was 39%.

Knowledge Gaps

The average day electrical consumption based on the research of Colon [23] shows that not all solar water heating systems are created equal. The ICS system on average does not perform as well as the flat plate systems, yet are promoted using the incentives programs. According to Moore [5] 22% of the known units installed under JEA’s solar initiative are ICS systems and there could be potentially more due to 16% of the total are classified as unknown. All of the literature shows promising results from solar water heating and in some cases even a positive effect on electrical peaks, but the question is left as to whether ICS systems reduce winter electrical peak loading.

CHAPTER 3
EXPERIMENTAL METHODOLOGY

To quantify the effects of an Integral Collector Storage solar water heater on peak electrical demand, a PROGRESSIVTUBE Systems PT-40-CN by TCT Solar was instrumented with a data acquisition and control system. The system was controlled to mimic typical household usage and sensors were extensively placed to acquire performance data. The experiment was sited at Beaches Energy Services in Jacksonville Beach, FL from the fall of 2010 through the spring of 2012. The effort was funded by American Public Power Association's (APPA) Demonstration of Energy & Efficiency Developments (DEED) program and JEA.

Experimental Details

Beaches Energy Services provided space and infrastructure at their vehicle maintenance facility, namely an unshaded plot of land, electrical power, water and protected space for tanks and data acquisition equipment. A solar collector was installed using the supplied water and electrical power for the system and subsystems. Sensors and data acquisition equipment were installed to monitor the system's performance. A controls strategy was implemented to mimic household usage and create a repeatable test.

Solar Collector

The PROGRESSIVTUBE PT-40-CN is made of eight 4" diameter copper tubes welded to interconnecting end pipes creating a continual series flow pattern. The smaller diameter interconnecting pipes connect the top of the lower pipe to the bottom of the next. The outer surfaces of the pipes are coated with a solar selective material to optimize solar radiation absorption and reduce losses. The case sides and back are made of aluminum. Rigid closed cell polyisocyanurate insulation lines the sides and back, and is placed between the collector tubes. The glass surface is double walled with a ¾” air space to create an insulating layer. The top glass is rated at 91% transmittance and the inner glass at 96%. The PT-40-CN has a collector face of four feet by eight feet providing 32 square feet of surface area total and has 40 gallons of internal storage. Figure 3-1 shows a cutaway of the PROGRESSIVTUBE ICS system [28].

Apparatus

The Department of Energy’s [29] guidelines for system sizing in the southern United States recommends 20 square feet of collector surface area for each of the first two residents and 8 square feet for each additional resident, with 1.5-2 gallons of storage for each square foot of collector area. The average residential dwelling is occupied by 2.8 people [19], thus requiring approximately 50 square feet of collector space. ICS solar systems are typically mated to a conventional domestic water heater, and for this experiment the system was plumbed in series with a dual element electric resistance 40 gallon unit manufactured by General Electric. Based on the collector surface area and the combined storage, the system mimicked a half scale test. The ICS was installed using aluminum struts with mounting brackets from the manufacturer and installed according to the manufacturer’s instructions. A platform measuring four feet by eight feet was constructed from two by six inch lumber and four by eight feet sheet of plywood. This platform mimicked a flat roof. The ICS and support structure can be seen in Figure 3-2.

Solar collectors installed in the Northern Hemisphere receive maximum sun exposure when installed facing south and year round performance is optimal when angled equal to the latitude of the location installed. To increase winter performance and protect from overheating in the summer, collectors are frequently installed up to 20 degrees greater than latitude [30]. For this experiment, the collector was installed facing due south and pitched at latitude +10 degrees which corresponds to a 40 degree above the horizontal or 10:12 equivalent roof pitch. Typical roof angles range in pitch from 4:12 to 9:12 or 18 to 37 degree angles [31].

Three quarter inch diameter copper tubing runs from the ICS for approximately four feet and is mated to half inch diameter rubber hose. The tubing and hose are wrapped in pipe insulation to minimize heat loss and provide an added level of freeze protection. The copper, hose and insulation are shown in Figure 3-3. The hose volume was calculated to be approximately 0.5 gallons which would be equivalent to approximately 20 feet of ¾ inch diameter copper tubing.

Infrastructure

As part of the in-kind financial contributions by Beaches Energy for the APPA DEED grant, an electrical meter was installed to provide electrical power consumption to the resistive elements of the water heater. A typical residential install would have 240VAC run to the unit, but the power available in this case was 208VAC. The vehicle maintenance shop has a carwash bay with a water filtration and recirculation system. By utilizing the water filtration system for the water supply, all water for the experiment was reclaimed and re-circulated minimizing water waste. For added water capacity and to aid in reduced temperature settling time, two 94 gallon tanks were added to the water recirculation loop. The overall system is shown in Figure 3-4.

Data Acquisition

Ambient data as well as performance data from the ICS system were acquired as part of the investigation. A Campbell Scientific model HMP45C weather probe measured the ambient temperature. A pyranometer from Eppley was installed on the same plane as the ICS to measure the solar irradiation available. Thermocouples from Omega Engineering were installed on the inlet and outlet of the ICS and also on the inlet and outlet of the auxiliary domestic water heater. An additional thermocouple was installed on the supply water line.

A piping and instrumentation diagram (P&ID) is shown in Figure 3-5. The thermocouples are labeled TCS for the supply line and TCP# for the passive system, with the # representing the corresponding assigned number. A positive displacement flow meter model C700 from AMCO (labeled FMP) measured the incoming cold water from the water supply line to the system. A power transducer that measured voltage and current was installed in the electrical meter can. The power transducer from CR Magnetics was used to measure the electrical power consumption of the resistive elements in the auxiliary water heater. A Campbell Scientific CR5000 data logger collected data every minute and recorded average values every fifteen minutes. The data was logged to a one gigabyte memory card and was downloaded onto a laptop periodically for review and analysis. The data logger is shown in Figure 3-6.

Controls

Three sprinkler timers were programmed to open a solenoid valve for certain times and durations, thus allowing flow through the system. The times and durations were based on the ASHRAE 90.2 [32] water draw profile, which is shown versus the projected draw profile in Figure 3-7. The use of the timers facilitated a completely automated flow program representing the hot water use of a typical family. In conjunction with the solenoid valve, a manual valve was set in a stationary position to throttle the flow so that the totals for the hours and days corresponded to the scaled system. The sprinkler timers are shown in Figure 3-8.

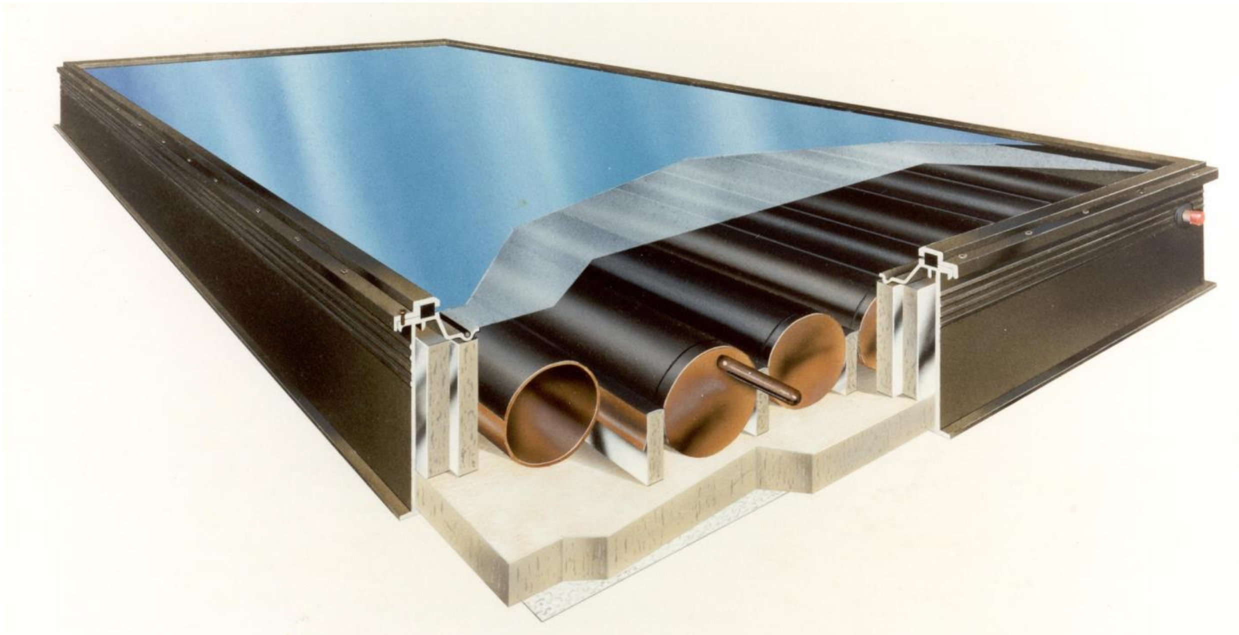

Figure 3-1. PROGRESSIVTUBE ICS system cutaway. (Source: [28] http://www.thesolarenergycenter.com/page/391300215. PROGRESSIVTUBE® passive solar water heating system.)

Figure 3-2. Integral collector storage solar water heating system mounted on the lower wooden platform support structure.

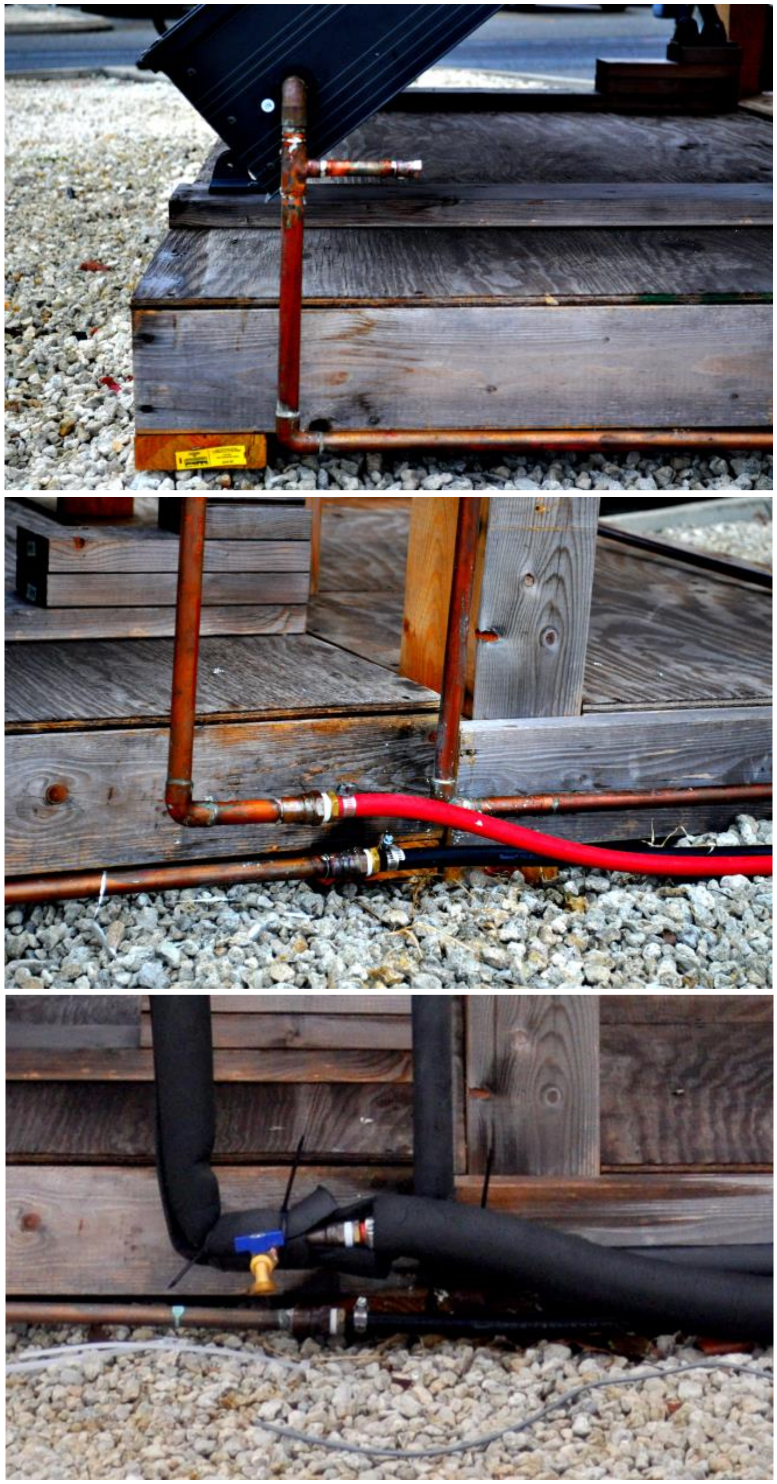
A
B
C

Figure 3-3. Pipework connecting the ICS system. A) Copper pipe soldered to ICS, B) EPDM hose connected to copper pipe, and C) pipe insulation reducing losses and protecting against freezing.

A

B

Figure 3-4. Water supply infrastructure. A) 94 gallon water storage tanks and B) water filtration and recirculation system.

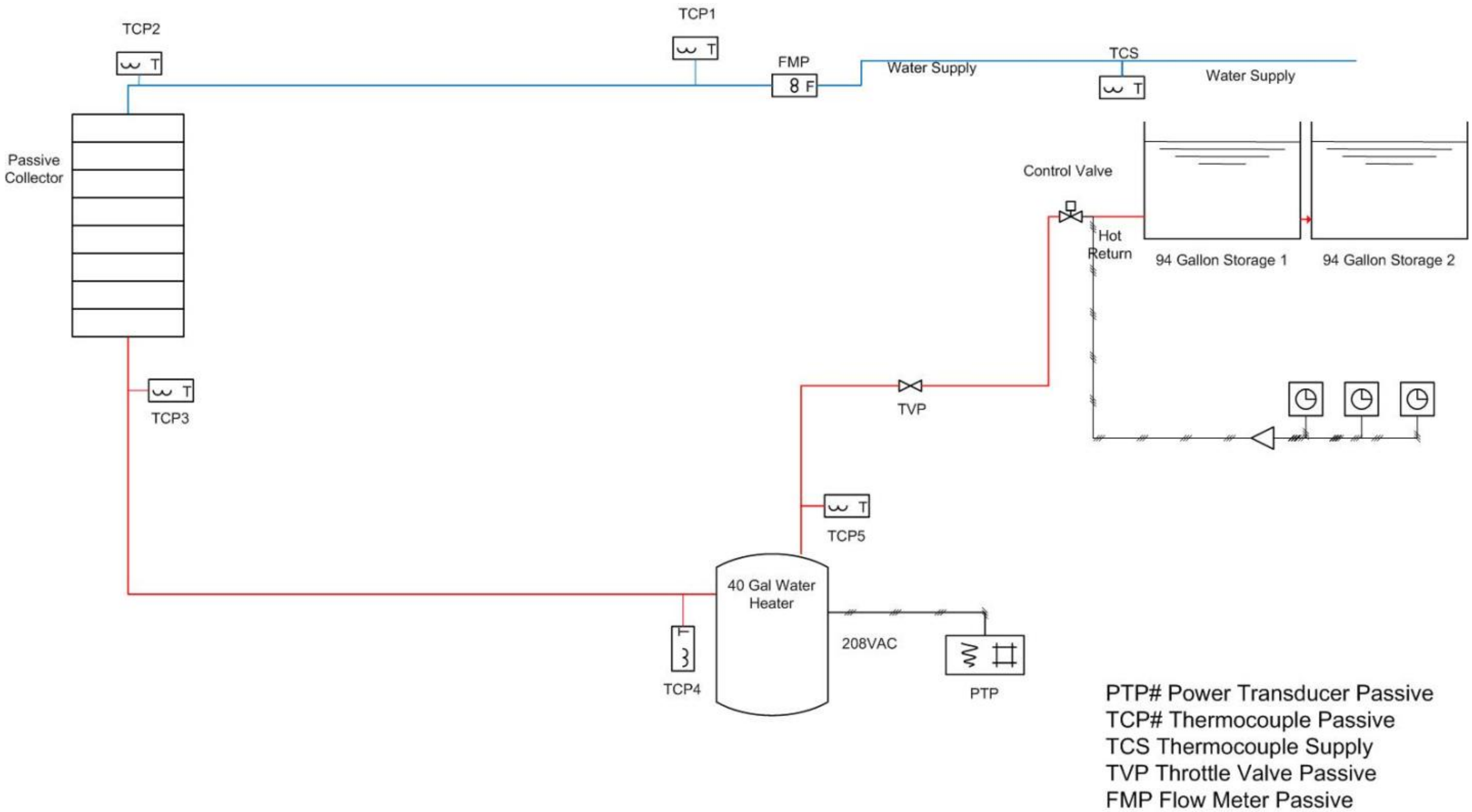

Figure 3-5. Piping and instrumentation diagram (P&ID) of the ICS solar system with infrastructure and data acquisition.

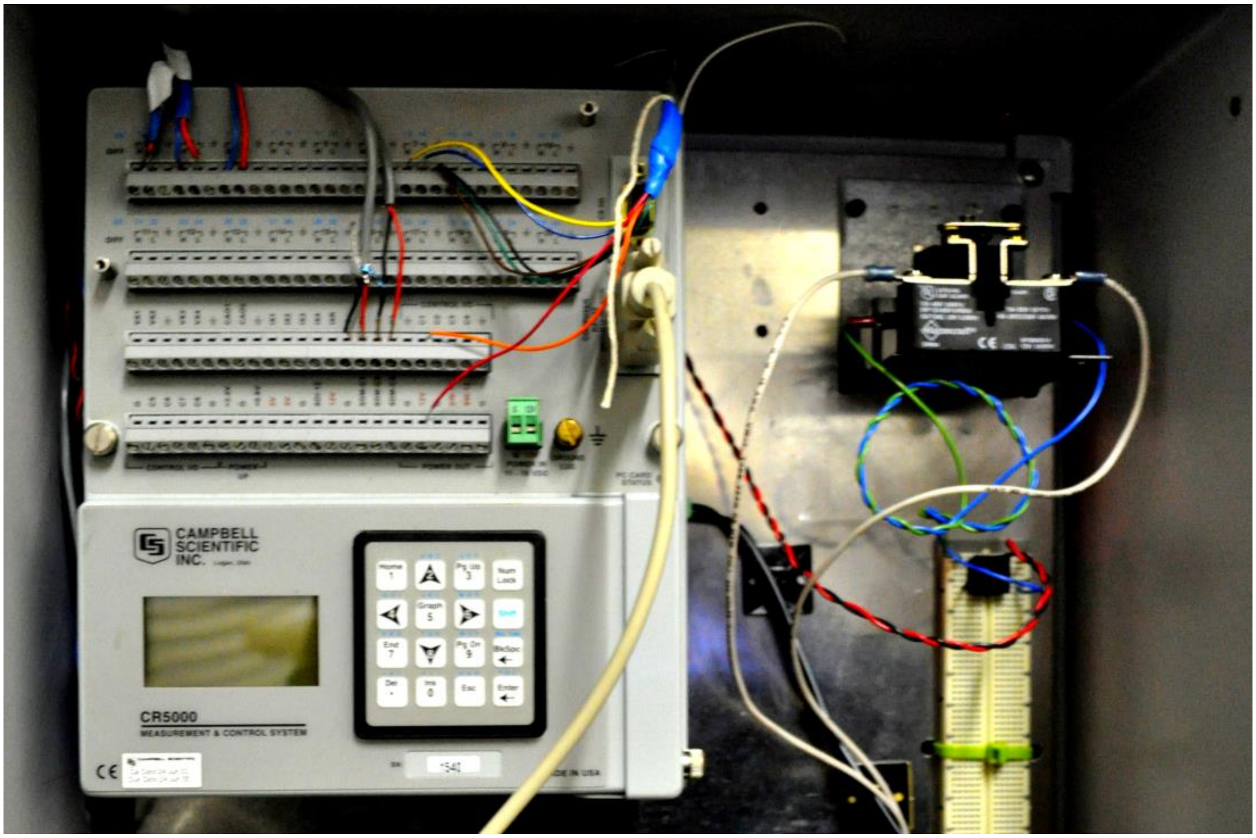

Figure 3-6. Campbell Scientific CR5000 data logger and relay with AC/DC rectifier for water draw controls.

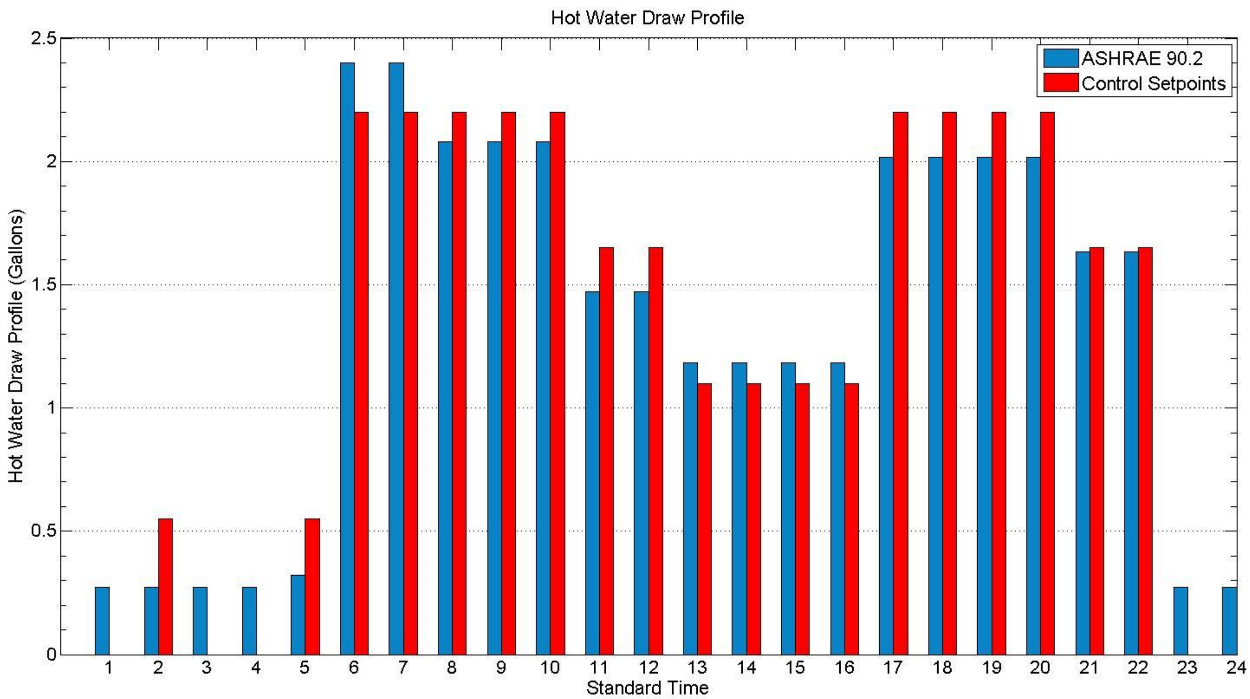

Figure 3-7. ASHRAE 90.2 hot water draw profile versus the projected draw profile.

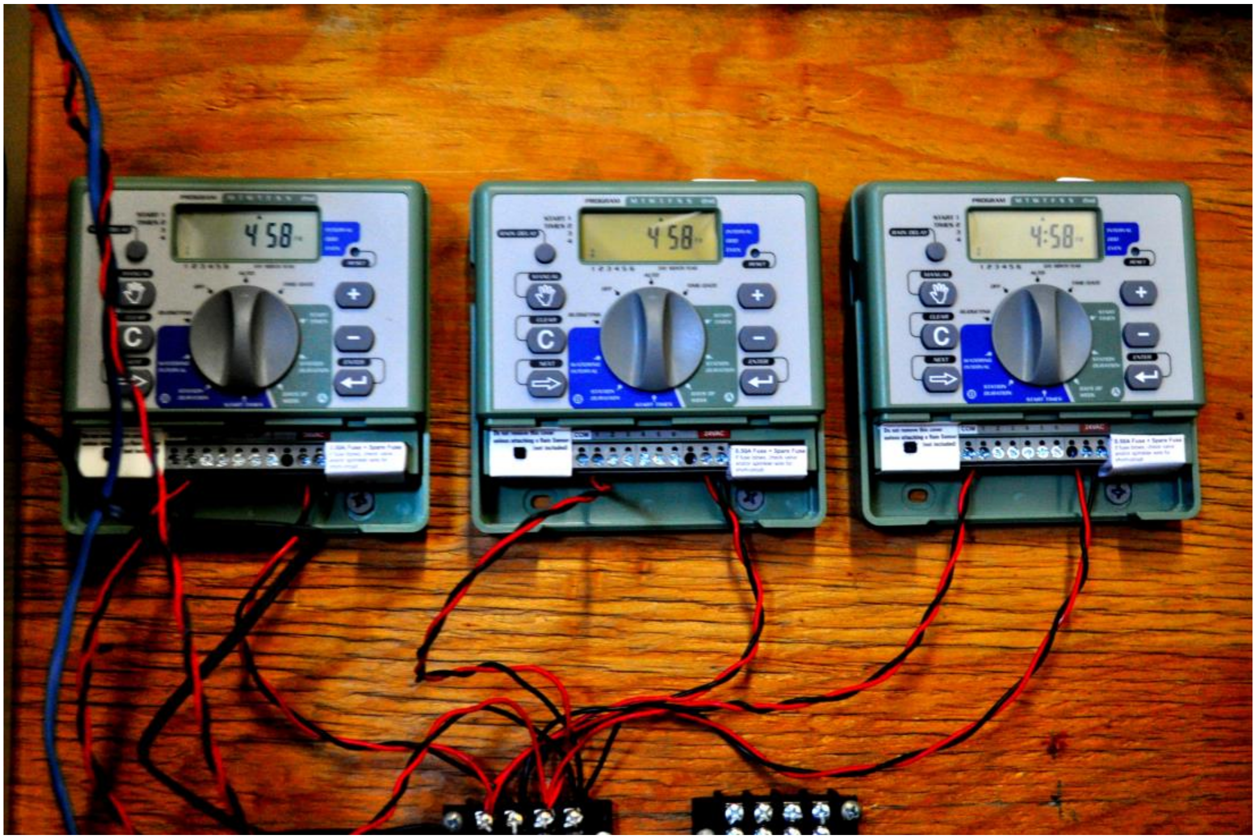

Figure 3-8. Sprinkler timers for water draw control strategy.

CHAPTER 4
EXPERIMENTAL RESULTS

The main area of interest for this investigation was the effect of an ICS system on winter peak demand. Winter peak demand typically is between 6 AM and 10 AM on the coldest winter mornings. Recreating residential usage was critical to appropriately measure the hot water available from the ICS under normal loading conditions. To appropriately quantify the effectiveness of the ICS, the temperature differential across the collector and across the complete system at a set flow rate was evaluated.

Ambient Conditions

To determine the effect of solar water heating on winter peak electrical demand, data was collected during the coldest section of the winter. Reviewing the data set collected from January 14 to January 27, 2012 shows that January 15 was the coldest morning. Because the model will be using weather data from NREL's TMY2 [33] (Typical Meteorological Year data set 2), which is explained further in the modeling chapter, the experimental weather data needs to be relatively similar to the published data that feeds the model. The ambient conditions collected and the TMY2 data for the same time period have a very similar pattern with very close high and low temperatures as shown in Figure 4-1. Figure 4-2 shows that the solar irradiation data for both the collected and published data are very similar from January 14 to January 17.

Temperature Data

Using January 14 to January 17 as the focal data of this analysis, the thermocouple data from the inlet and outlet of the collector is presented in Figure 4-3. The data presented has been averaged and grouped into hourly sections. The graph reveals that at no point is the outlet temperature lower than the inlet temperature, which is evidence that the collector was transferring heat to the water.

There is potential for the inlet to the collector to be colder than the ground temperature due to convection and radiation losses to the cold ambient air from the long inlet piping runs. Figure 4-4 shows that the temperature of the inlet piping to the collector is never more than 2°C less than the water supply temperature during the 6 AM to 10 AM time window, indicating minimal heat loss. The water supply temperature measured is 15.3°C. This is lower than the published literature. Parker measured tap water in February at 19.4°C [20]. Colon measured the average supply temperature to be between 17°C and 18°C during the January and February months [23].

There is potential to lose heat through the piping runs from the collector to the inlet of the conventional electric water heater, but the hose was insulated to reduce losses. Figure 4-5 reveals that the temperatures between 6:00 AM and 10:00 AM for all three mornings are higher at the water heater inlet than the ICS outlet. This difference is approximately 5°C during the morning peak for January 14th and 15th and is attributed to conduction through the piping connected to the water heating tank.

The temperature rise across the electric water heater, shown in Figure 4-6, indicates that the outlet exceeded the inlet temperatures during 6:00 AM to 10:00 AM. This data suggests that the electric water heating element is heating the water during the peak times.

Flow Data

The flow was controlled by opening a solenoid valve at the top of the hour in response to the sprinkler timers. The flow meter data is the number of gallons used during the course of each hour and is therefore in units of gallons per hour. Reviewing the flow meter data for January 14 to January 17 shows that the flow meter was unresponsive. A parallel test for another solar experiment was also collecting flow data, so a correlation was made to replace the lost data. The calculated data was plotted against the projected flow plan from the ASHRAE 90.2 [32] standard draw profile in Figure 4-7, and shows a close comparison.

Energy Data

The electrical power data measured by the CR Magnetics power transducer is shown in Figure 4-8. The data indicates that the electricity usage is weighted more towards the morning, particularly on January 14 and 15, where the magnitude of the average power along with the frequency of the cycling is greater than any other time during the day. During the time of the experiment of greatest interest the average power draw is 2006.6 watts. At this rate, the electric water heater is consuming approximately 8 kWh of electricity between 6 AM and 10 AM.

The rate of energy within the system was calculated using the flow rate and temperature differentials across various components. This calculation required the specific heat of water and the energy equation.

$$\dot{Q}\ \text{(Watts)} = \dot{m} C_p (\Delta T)(1\ \text{hr}/3600\text{s}) \tag{4-1}$$

$$\dot{m}\ \text{(grams/hour)} = (X\ \text{gal/hr})(3790\ \text{grams/gal}) \tag{4-2}$$

$$C_p\ (4.181\ \text{J/g K}) \tag{4-3}$$

$$\Delta T\ \text{(K)} \tag{4-4}$$

Using Equation (4-1) the average energy rate of the solar collector for the morning of January 15 was calculated and is shown in Figure 4-9 plotted with the electric power draw of the electric water heater. The temperature differential used for the calculation was the difference between the measurement at the inlet and outlet of the collector (TCP3 and TCP2 on the P&ID in Figure 3-5). The calculation shows the collector on average is producing 1605.4 watts per hour, which over the course of 4 hours is a 6.4 kWh contribution.

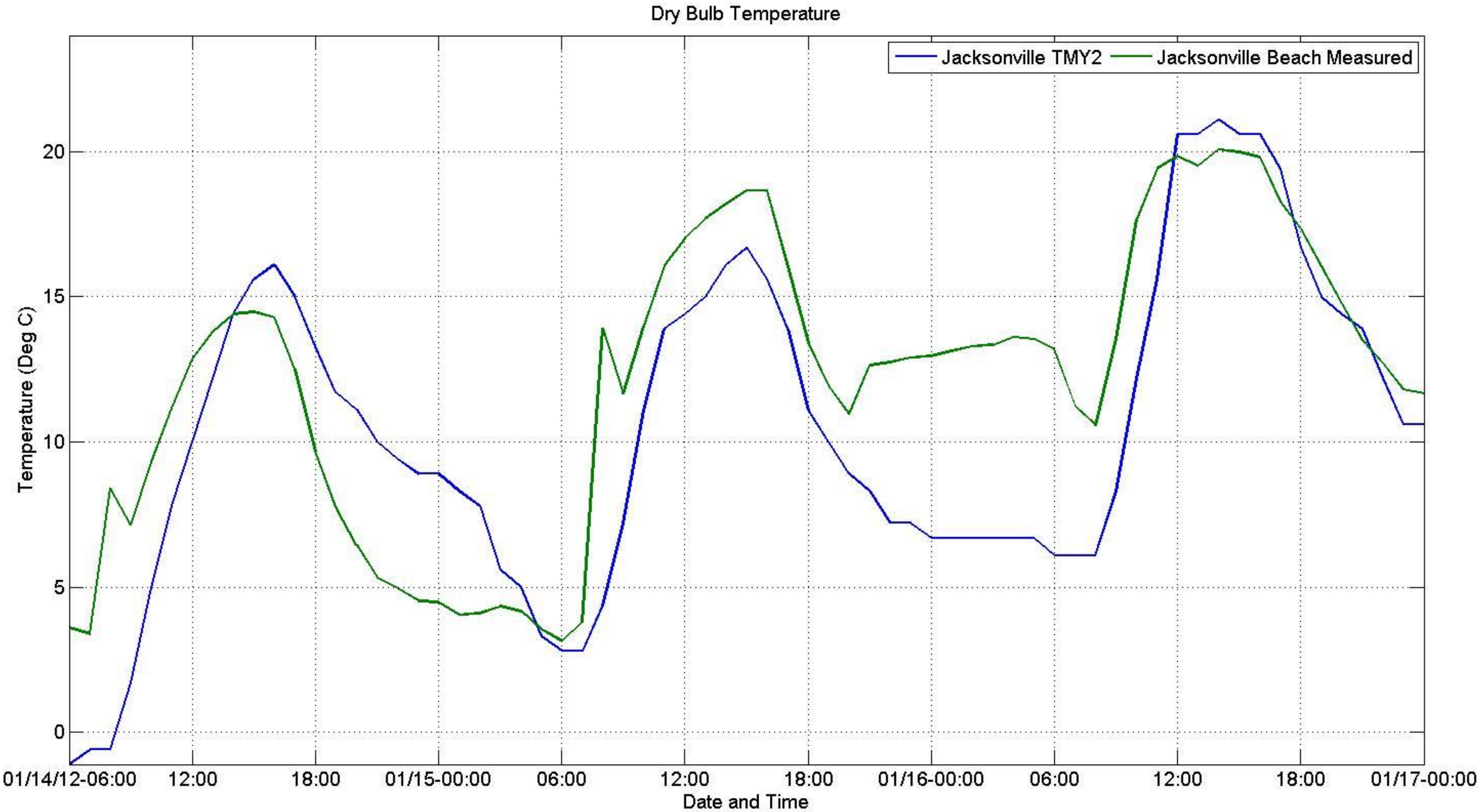

Figure 4-1. Dry bulb temperature measured versus NREL's TMY2 data for Jacksonville for January 14 to January 17.

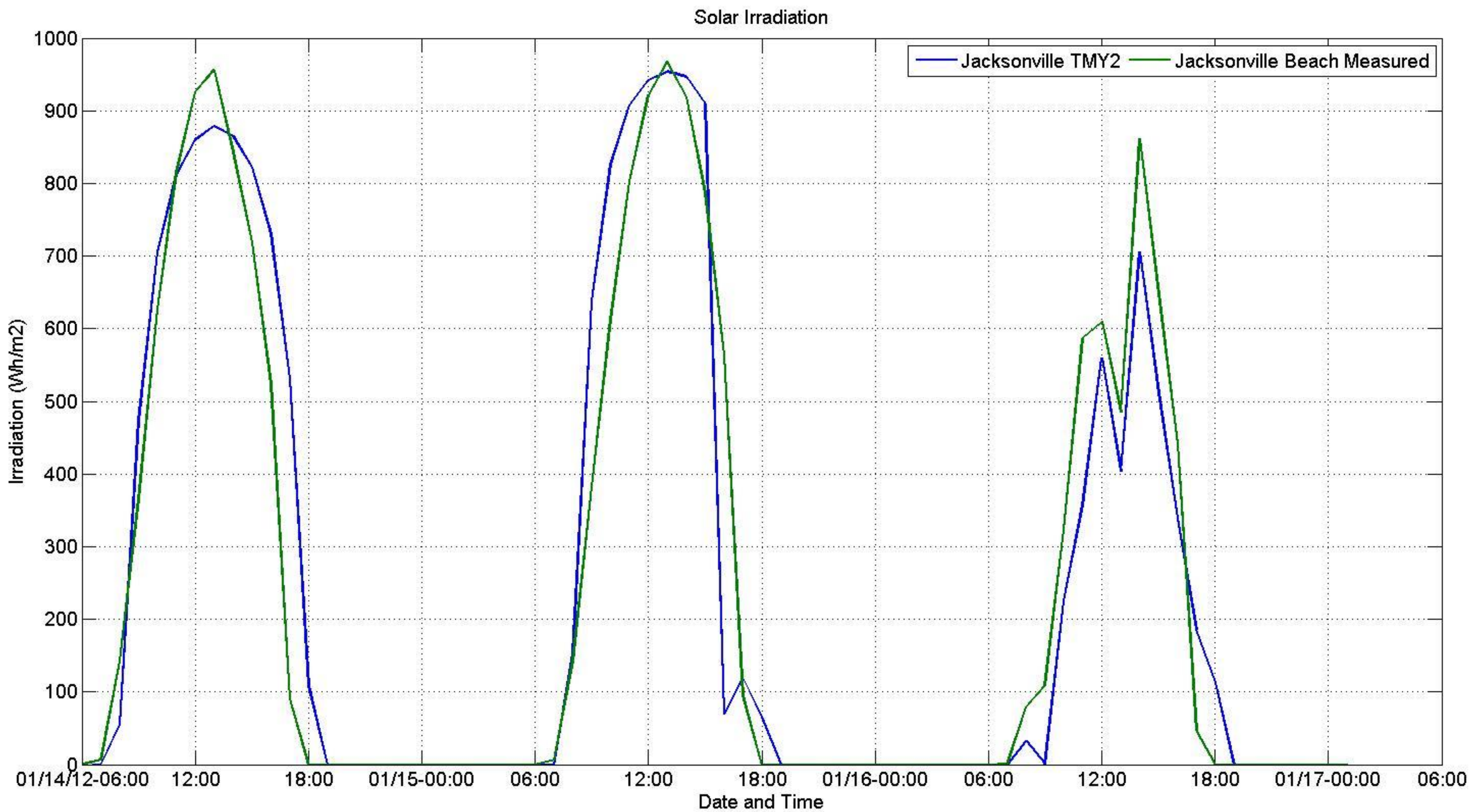

Figure 4-2. Solar irradiation measured versus NREL's TMY2 data for Jacksonville for January 14 to January 17.

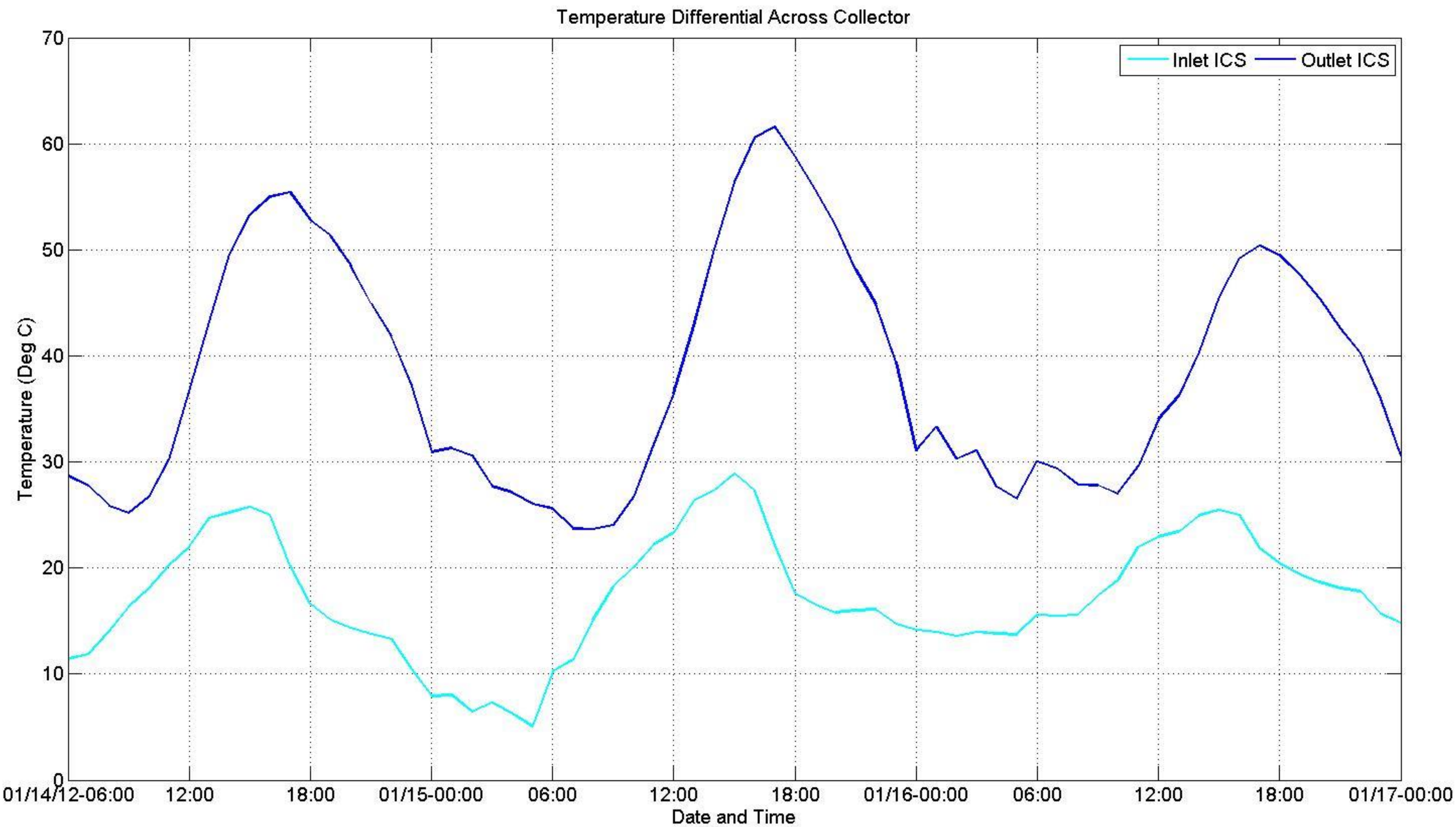

Figure 4-3. Measured temperatures at inlet and outlet of ICS for January 14 to January 17.

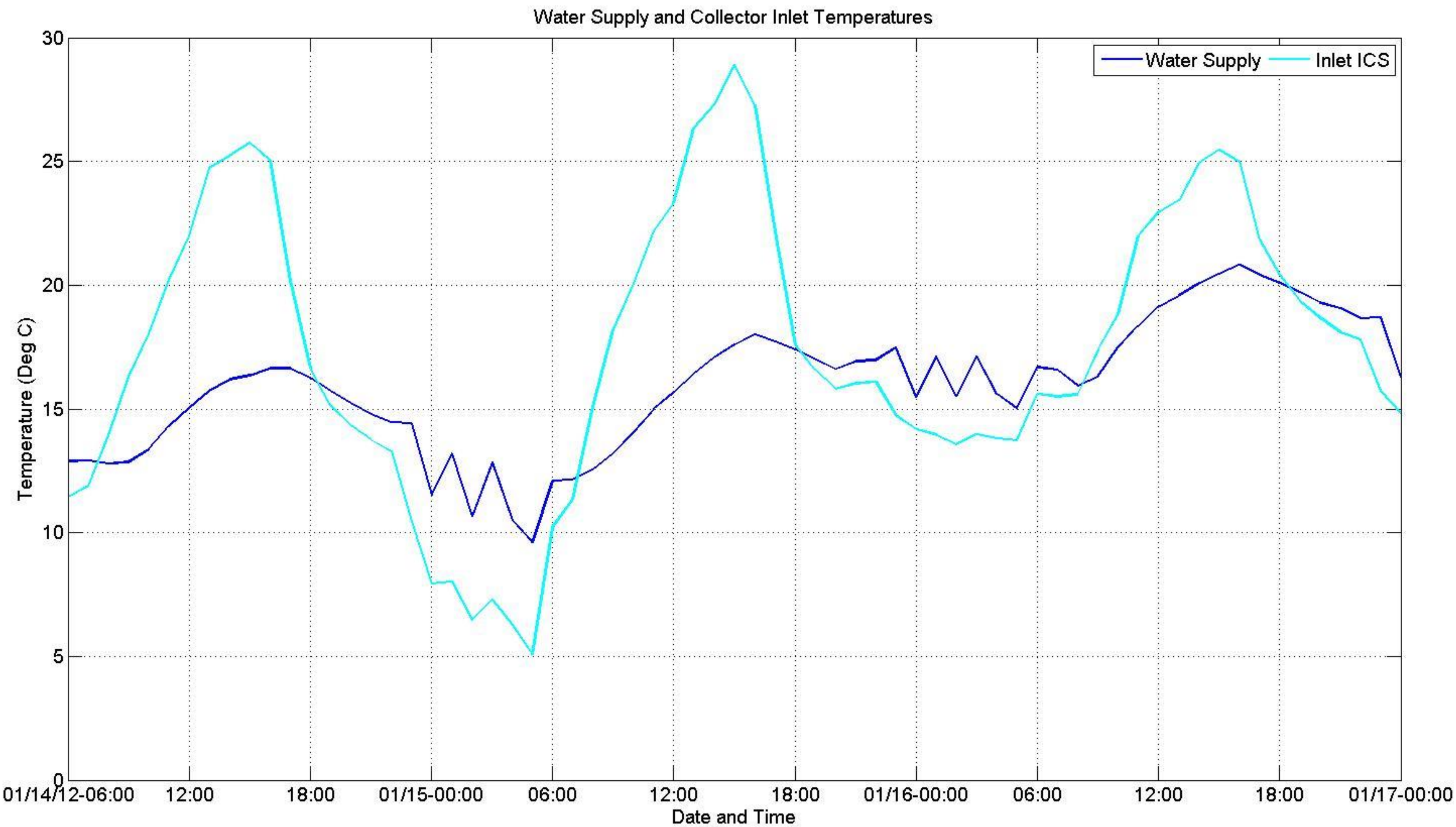

Figure 4-4. Measured temperatures of water supply and inlet to ICS for January 14 to January 17.

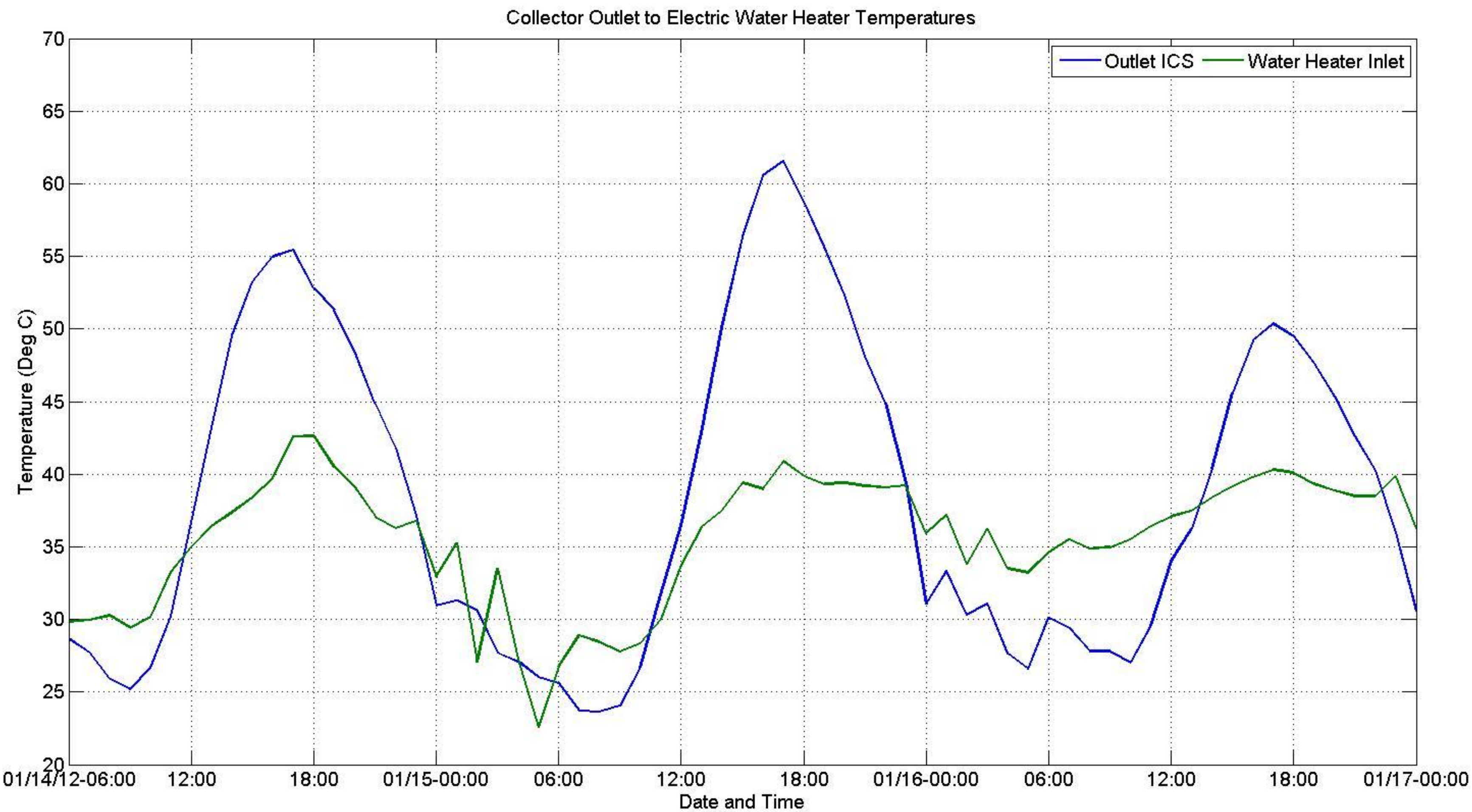

Figure 4-5. Temperature measurement comparison between the outlet of the collector and the inlet of the electric water heater from January 14 to January 17.

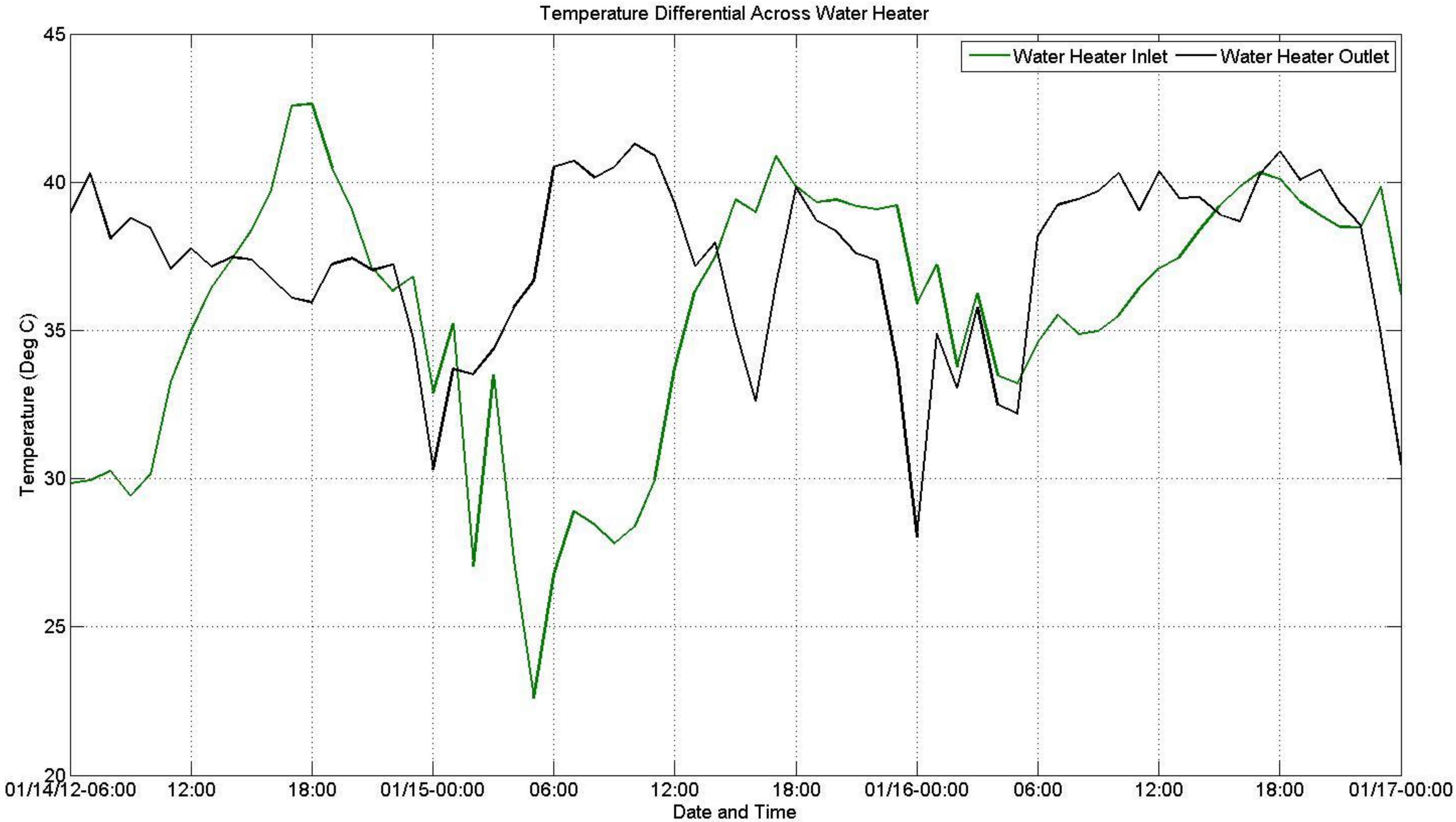

Figure 4-6. Comparison of the inlet and outlet temperature of the electric water heater from January 14 to January 17.

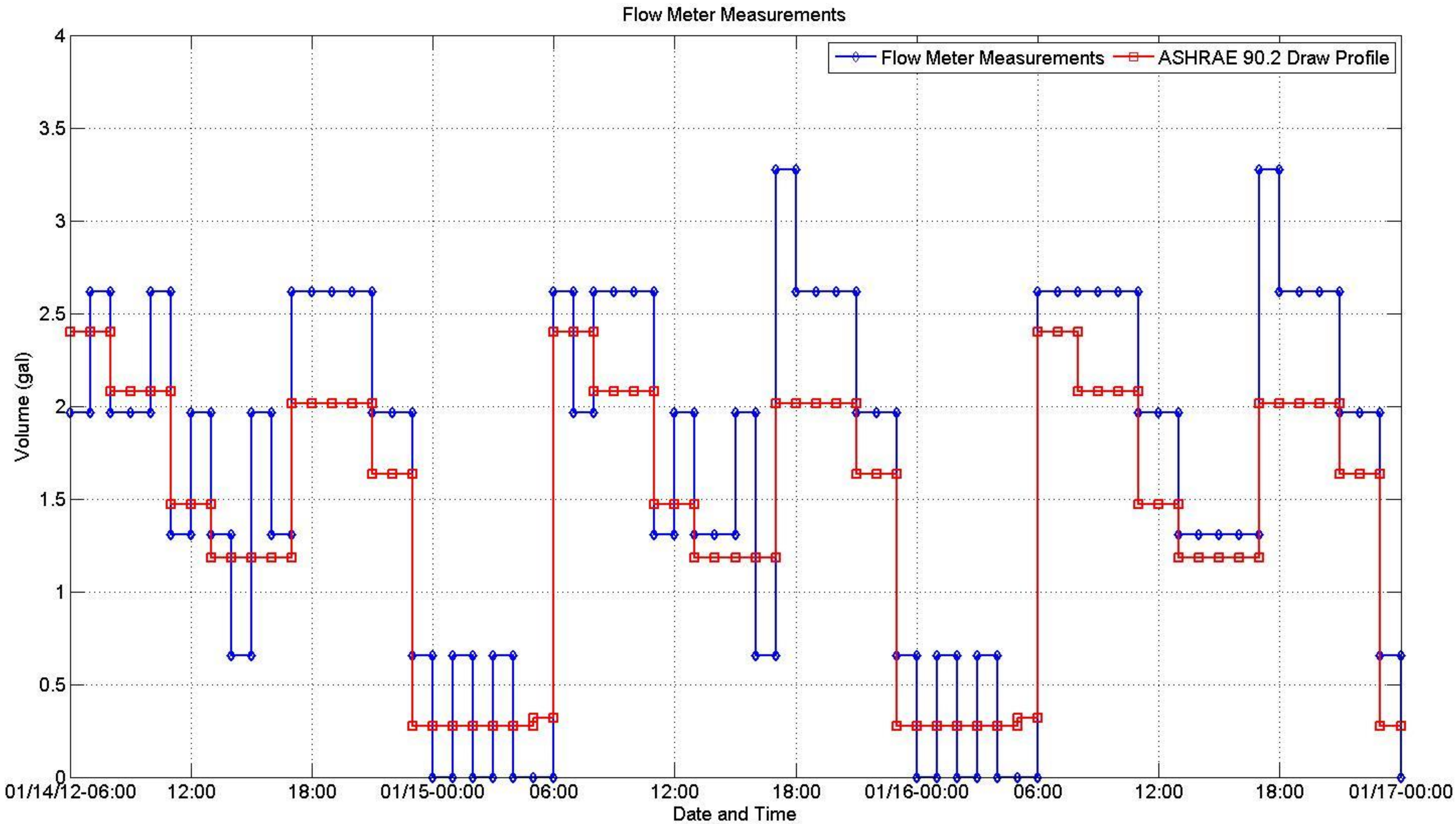

Figure 4-7. Flow meter data compared to ASHRAE 90.2 draw profile from January 14 to January 17.

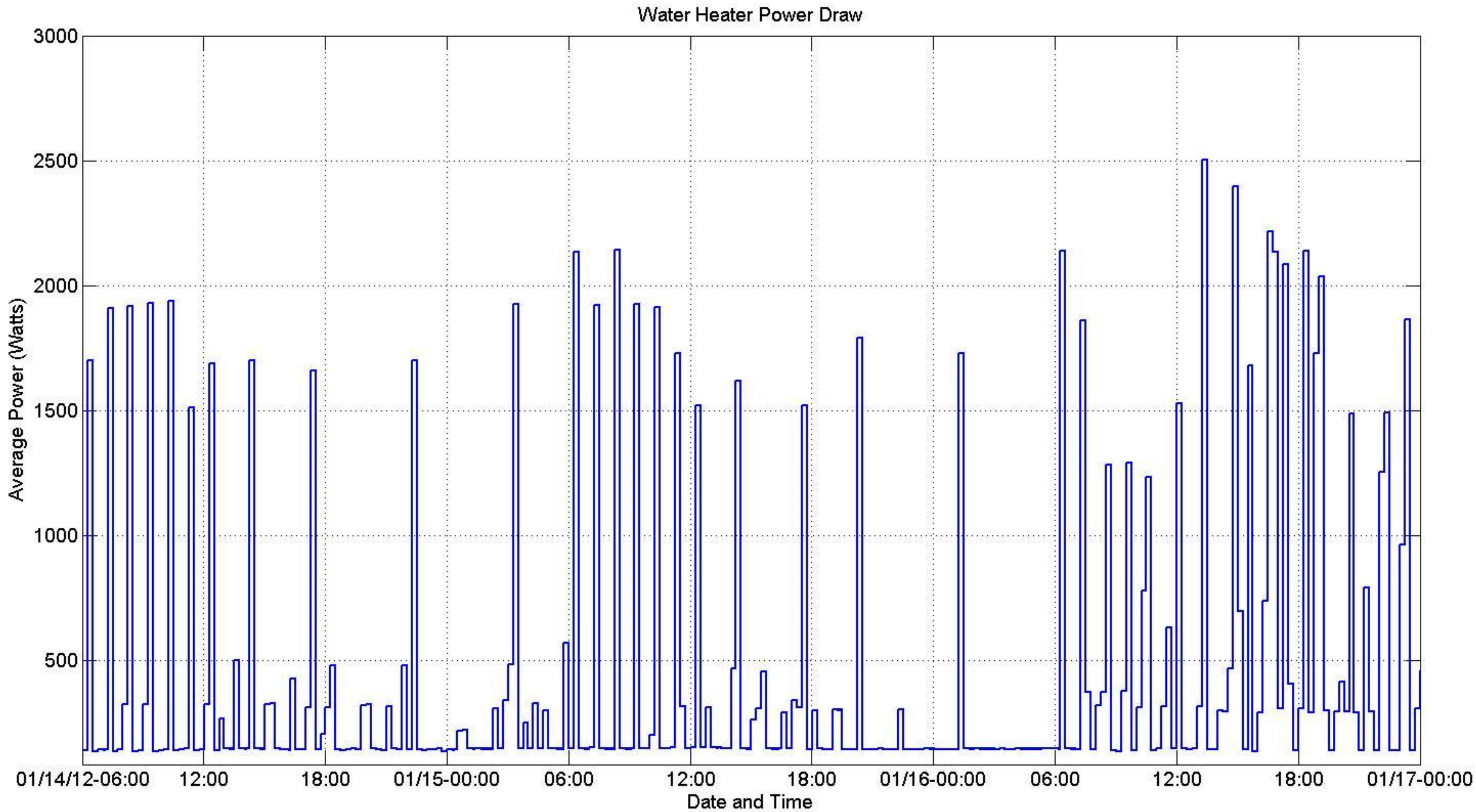

Figure 4-8. Electricity consumed by the auxillary water heater as measured by the power transducer.

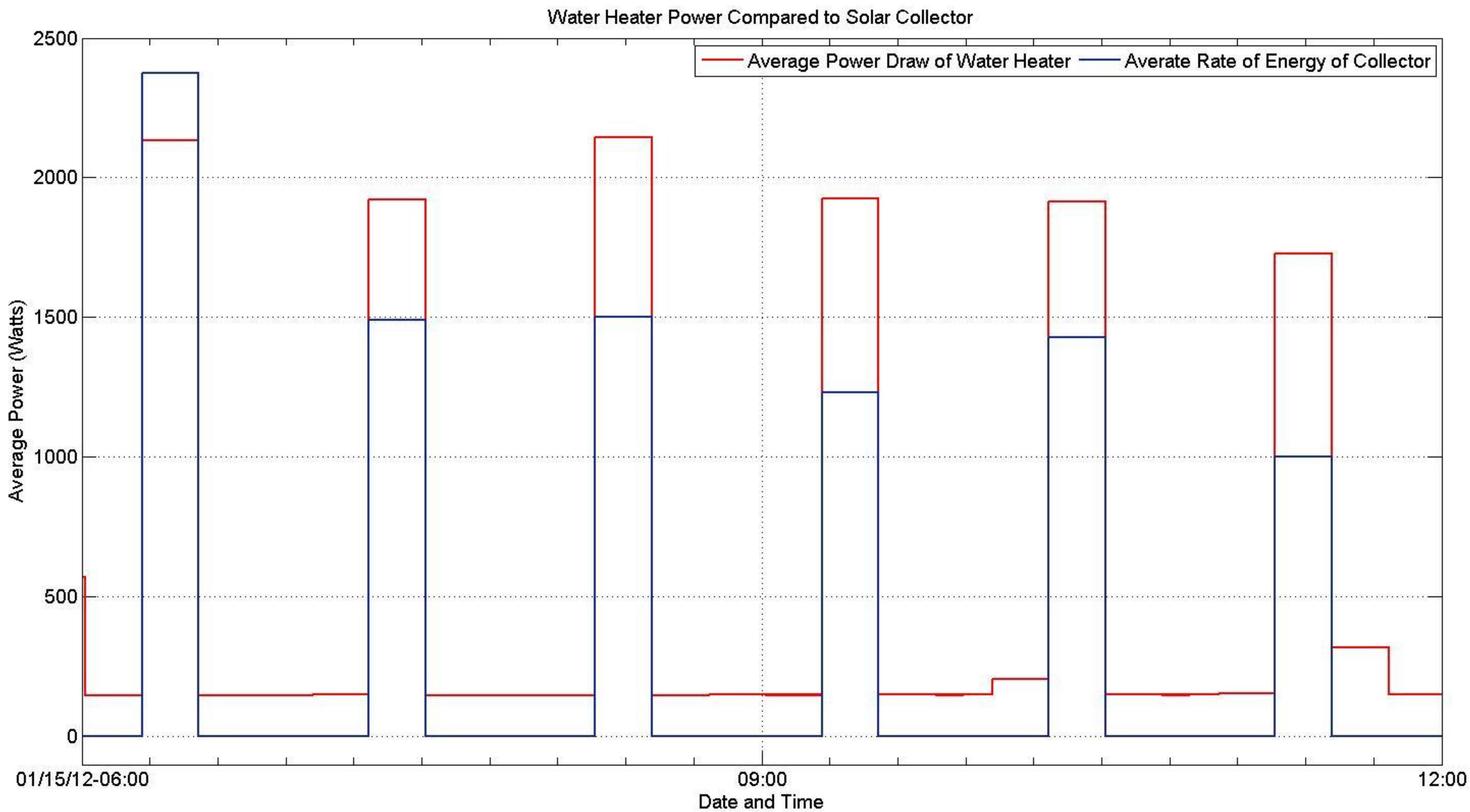

Figure 4-9. Energy rate calculations based on the flow rate and temperature differential on the morning of January 15.

CHAPTER 5
MODELING

TRNSYS is a robust modeling platform with a long history of providing reliable performance predictions [21,22]. The software model for this solar application opens up opportunities to test the effectiveness of the experiment in varying locations, with a different system sizes and at other times of year. The Department of Energy’s Building America program in conjunction with National Renewable Energy Lab (NREL) released a software program built on a TRNSYS platform to model solar water heating system installations for the purpose of evaluating the effects of solar water heating on electrical and gas consumption. Permission from NREL has been granted to use this model for the research presented [17].

Weather, Hot Water Draw and Simulation Model

The graphic user interface for the model is made up of tabs with selectable options and cells to adjust the default numbers. The first step in the model is to set the simulation parameters for a given duration. There are multiple options ranging from one day to one year. For specific simulations, month and day selections can be input. The second variable is the weather station locations. Weather data from 239 cities collected from 1961 to 1990 is organized in a series of files that make up the NREL TMY2 data set. TMY2 stands for Typical Meteorological Years and the 2 is that it is NREL’s 2nd set of published weather data. The water draw profile is the third input for the simulation. A user input profile is an option, so the hot water draw profile from the ASHRAE 90.2 standard was entered. Lastly, the daily hot water consumption was input. To most closely model the experimental setup, the duration was set to run for one week beginning January 14, using the data set from Jacksonville, Florida with the ASHRAE 90.2 profile and a hot water consumption total of 39 gallons.

System Model

The second section of the model requires system information input. There is flexibility to operate basic systems with default settings or to enter into the user-input selection to further customize the model. All of the ICS models have user adjustable inputs for the following: collector top surface area, height of enclosure, water storage volume and the number of collectors plumbed in series.

Figure 5-1 shows the performance of the system when modeled as a selective surface ICS with predominantly default settings. The user input values for the basic model include the collector size of 32 square feet, 40 gallons of internal storage and a total depth of 8 inches. The installation variables include orientation parameters, namely the slope of the collector (0=horizontal and 90=vertical) and the azimuth of the collector (0=south, 90=due west, -90=due east). In this case the slope was set at 40.20 degrees and the azimuth was set to zero because the experimental setup was Latitude plus ten (30.2+10=40.2) and was facing due south. At first glance the modeled results seem very optimistic compared to the experimental data. The first model run with the basic inputs performed with a 15° to 20° Celsius higher value on the collector return during the peak temperature output.

To better match the system in the experiment, the User-Input ICS was selected for the second iteration. The User-Input ICS adds absorptance, index of refraction, cover extinction and thickness, air insulation space between top layers and emissivity variables. Using the specifications from the data sheet from the manufacturer [34] and from Florida Solar Energy Council’s Summary Information Sheet [35] the inputs were adjusted to better represent the specific ICS. Figure 5-2 shows the updated model performance. The added variables helped close the gap between the model and the experiment, but the differences were still about 20%. An audit of the system was undertaken to better understand this difference.

Anchoring the Model

The first variable considered was in regard to the installation. The experiment uses a collector mounting structure from a flat roof installation kit. This variable leaves the back of the collector exposed to the ambient air and the potential for heat loss due to free convection is much greater. The model does not have an input for this installation variable. To test whether heat loss to convection could make up the 20% difference, a series of calculations were completed. Using Equations (5-1) through (5-5) provided a basis for a basic free convection analysis [36].

$$g \rightarrow g\ \cos\theta \tag{5-1}$$

$$\mathrm{Ra_L} = \mathrm{Gr_L}\,\mathrm{Pr} = \frac{g\beta(T_s - T_\infty)L^3}{v\alpha} \tag{5-2}$$

$$\mathrm{Nu_L} = \frac{hL}{k} = \left\{0.825 + \frac{0.387\mathrm{Ra}_L^{1/6}}{\left[1+(0.492/\mathrm{Pr})^{9/16}\right]^{8/27}}\right\}^2 \tag{5-3}$$

$$q = hA_s(T_s - T_\infty) \tag{5-4}$$

$$(\Delta T) = \frac{q}{\dot{m}C_p} \quad (5\text{-}5)$$

For the calculations the average solar collector temperature at the peak of January 14 was considered the surface temperature (T_s). The free convection calculation revealed a 32°C reduction from the outlet as a result of the back of the collector being exposed. Due to the severity of the reduction a more specific heat transfer resistance network was calculated using Equations (5-6) through (5-9) [36].

$$R_{t,cond} = \frac{L}{kA} \quad (5\text{-}6)$$

$$R_{t,conv} = \frac{1}{hA} \quad (5\text{-}7)$$

$$R_{tot} = \sum R_t \quad (5\text{-}8)$$

$$q = \frac{T_{\infty,1} - T_{\infty,2}}{R_{tot}} \quad (5\text{-}9)$$

The resistance calculations revealed that the conduction through the insulation and aluminum combined with the free convection only account for slightly more than a 3°C reduction in output. An investigation of the source code from the model revealed insulation assumptions and values. This series of calculations disproves free convection to be the predominant difference between the experiment and the model.

The next variable explored was the degradation of performance as a result of collector surface residue. Further review of the public literature [37] revealed a claim of 30-40% reduction in performance can be expected as a result of salt, dirt and birds. The author of the publication recommends a panel be cleaned ideally every 3 months and at the least every 6 months. The panel under test was purchased in 2007, has been in a variety of environments, and has never been extensively cleaned. The test location is in Jacksonville Beach and is located at ground level in an environment near gravel parking lots. Both salt air and gravel dust have the potential to be strong contributors to performance degradation. The cleaning company's recommendation and estimated losses, as well as the installed environment, led to operating the model with degraded absorptance values.

The published absorptance value from the manufacturer is 0.91. At a 25% reduction, the modeled output and the experimental data for the collector output was within 2°C of each other on the peak outputs and within 5°C on the low outputs. On the high value outputs, that is about a 3.5% difference. The collector return pipe length was adjusted from 50 feet to 125 feet due to increased losses from outdoor installation versus an attic or garage space. The model results closely match the experimental temperature values. The added length lowers the temperature as a result of the increased losses through the increased surface area. Figure 5-3 shows the updated model temperatures for January 15 to January 17. Figure 5-4 represents the same model, but displays January 15 solely. Figure 5-5 is the experimental data for the same time period. The ICS inlet temperatures from the experiment are consistently lower than the expected or modeled inlet temperatures, therefore the ICS average temperature is lower. The peak ICS outlet temperature and the collector delivery temperature of the model and experiment follow each other closely, so the current set points create the baseline for predicting performance using the model.

Auxiliary Heat

In a typical installation, an ICS is plumbed upstream in series with a conventional electric resistance water heater. To appropriately model the effects that a solar water heater has on the electrical usage, the model requires some auxiliary heat information. In this case, the unit is an electric storage tank, as opposed to gas or tankless, and has 40 gallons of storage. The energy factor is 0.92. The unit has a height of forty six inches and has two electrical resistant heating elements. Each heating element has 4500 watt capacity. The set point for each element was input. To match the experiment, both units were set at 41°C. The setting on the actual unit was for 52°C, but the measured temperature was 41°C. The difference is attributed to the voltage feed of 208VAC instead of 240VAC.

Figure 5-6 shows the modeled water heater cycles on and off very frequently during the morning peak time and comes on once in the evening. The model has summarized data that writes to excel files to create graphs.

Figure 5-7 shows on an average January day the ICS is detrimental to the morning peak between 6 AM and 8 AM, but begins to contribute from 8 AM to 10 AM.

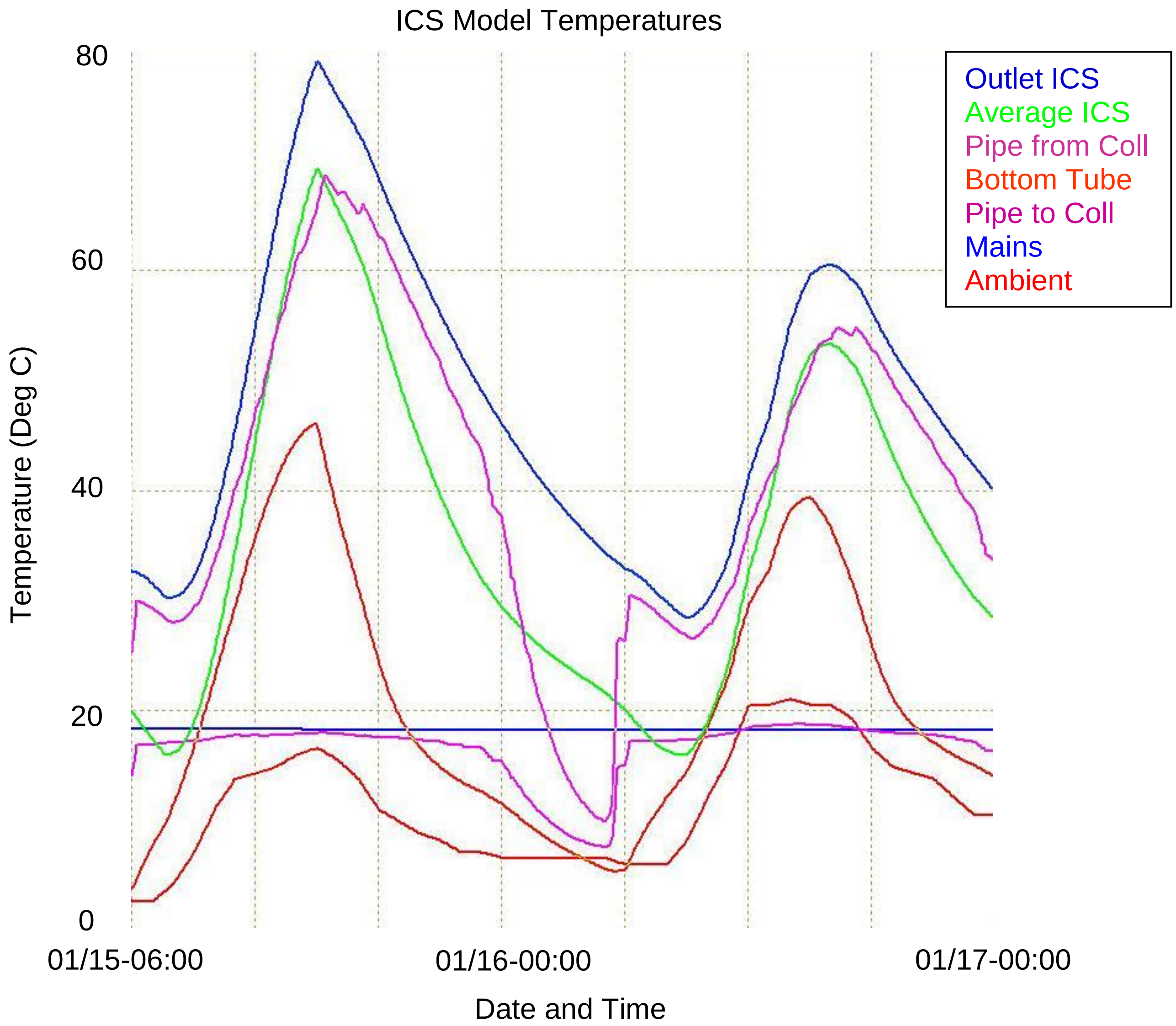

Figure 5-1. Selective surface ICS model temperatures.

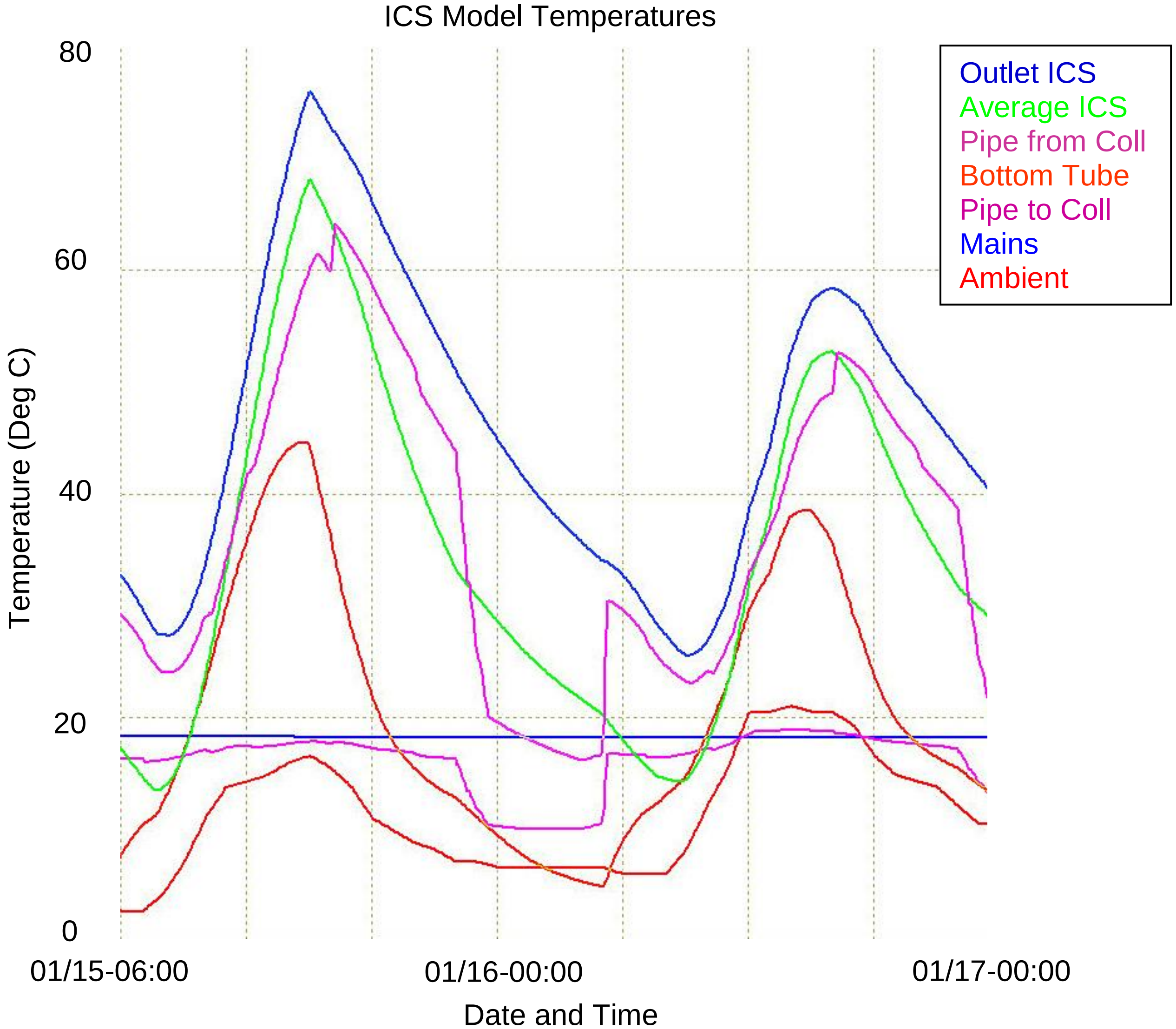

Figure 5-2. User-input ICS model temperatures.

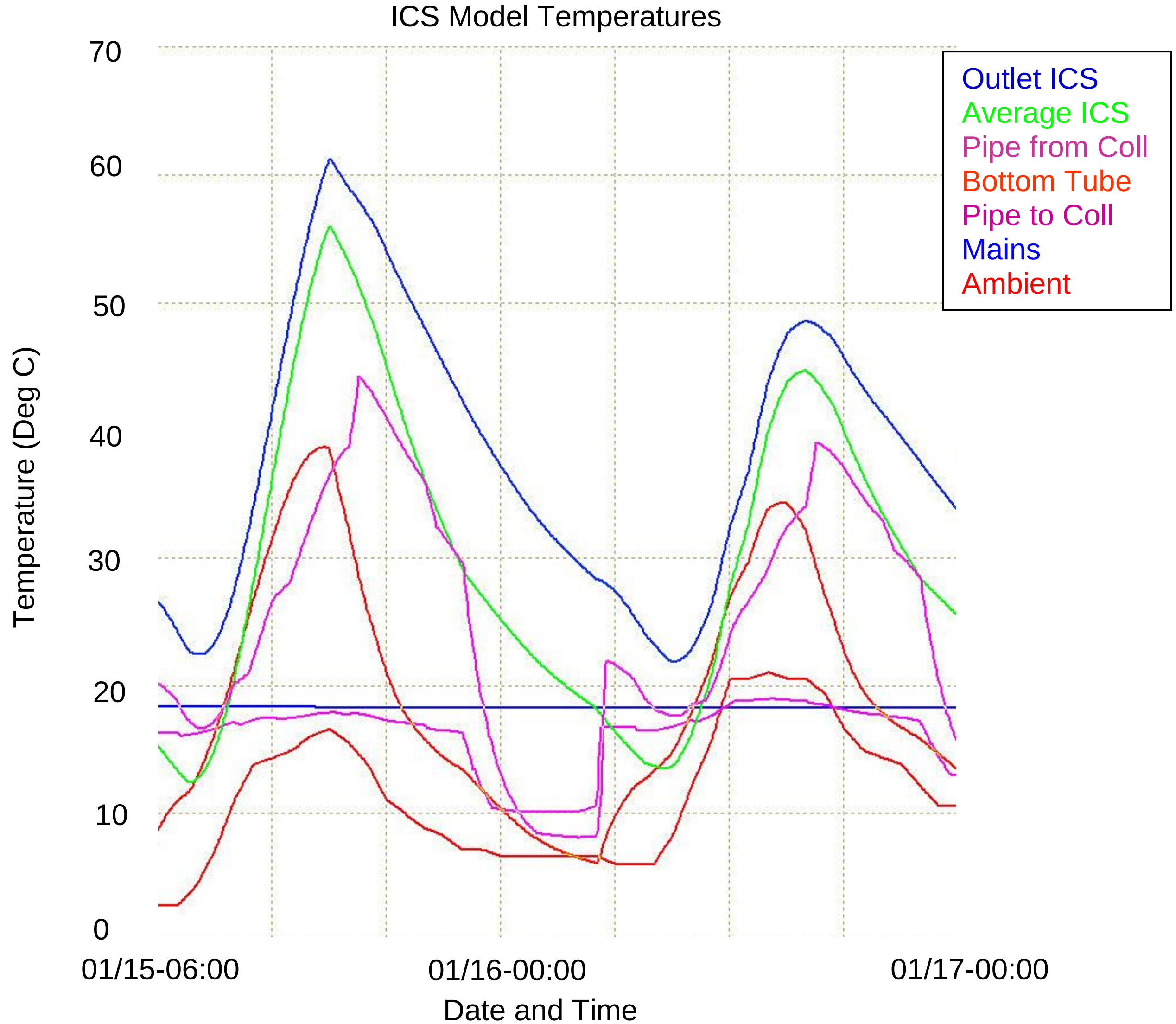

Figure 5-3. User-input ICS model temperatures with reduced absorption and lengthened return pipe.

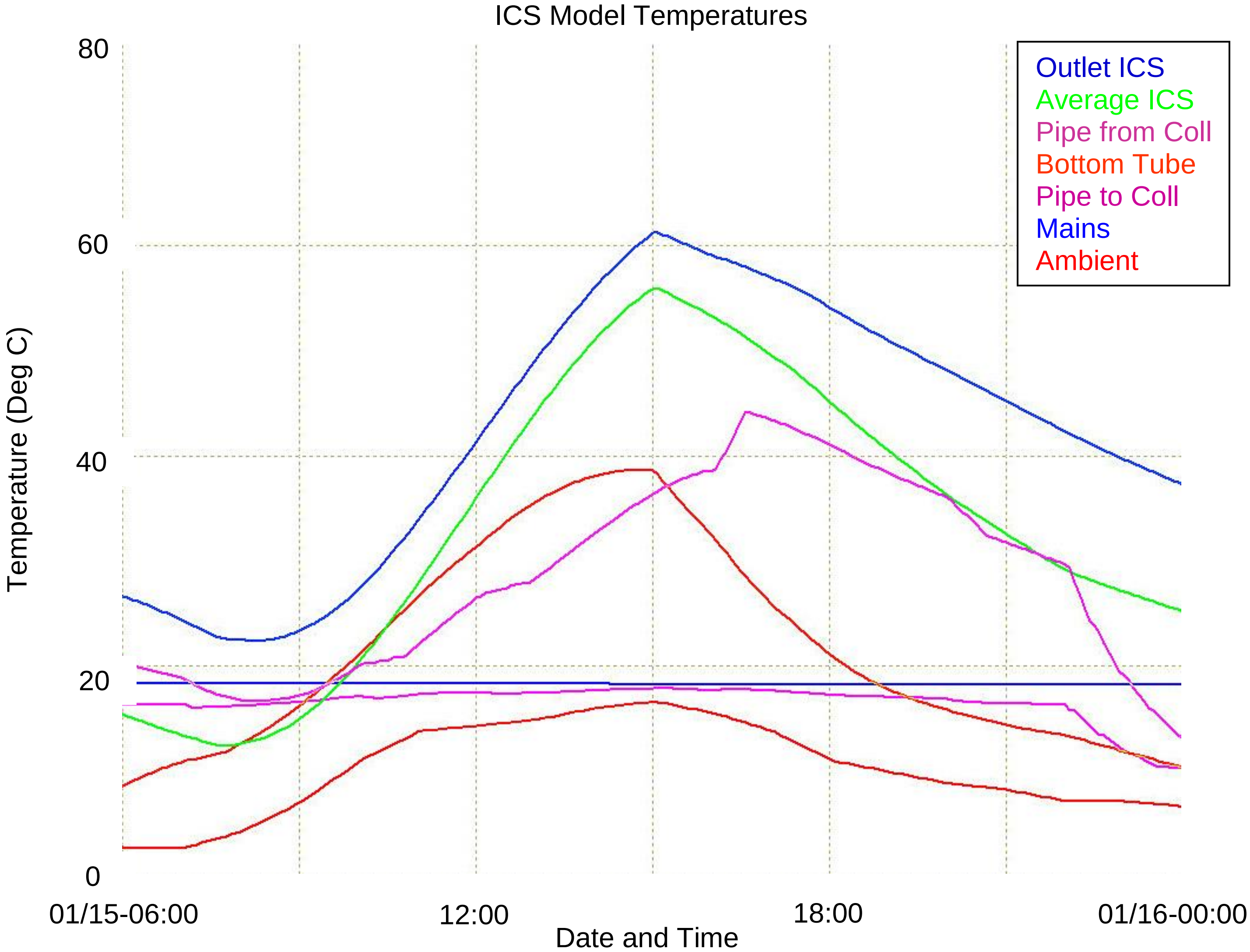

Figure 5-4. User-input ICS temperatures for January 14.

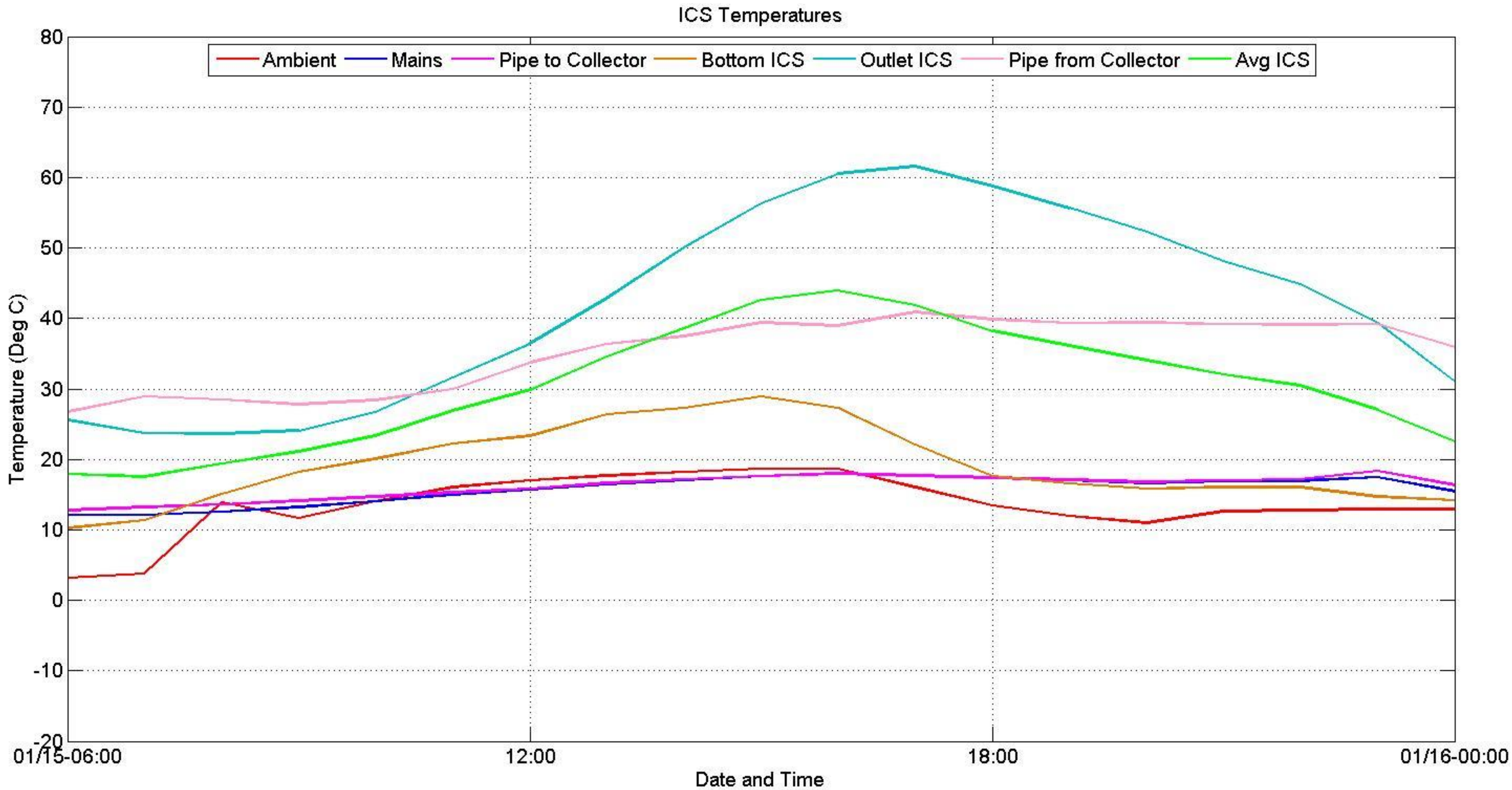

Figure 5-5. Experimental data temperatures January 15.

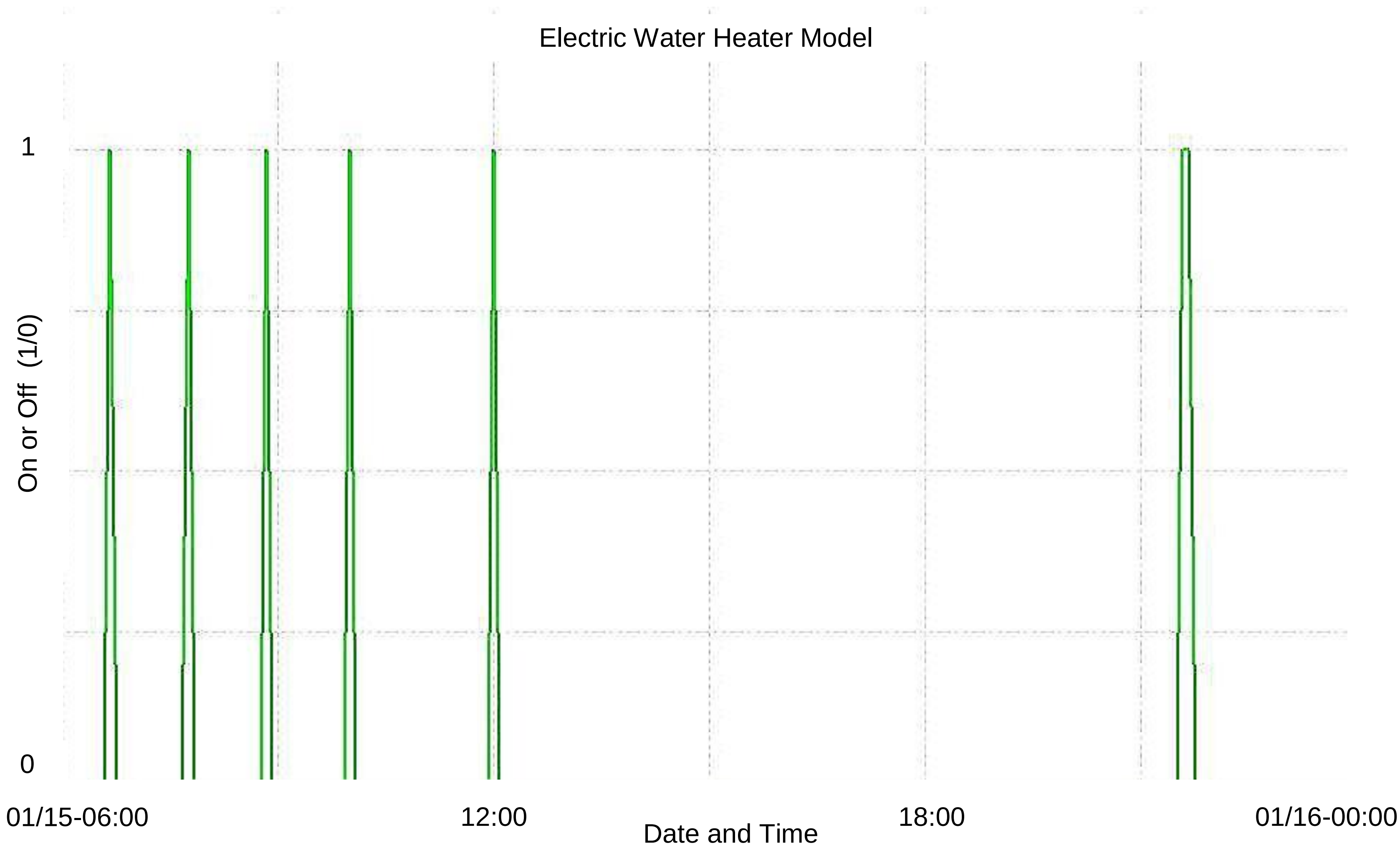

Figure 5-6. Electric water heater model for January 15.

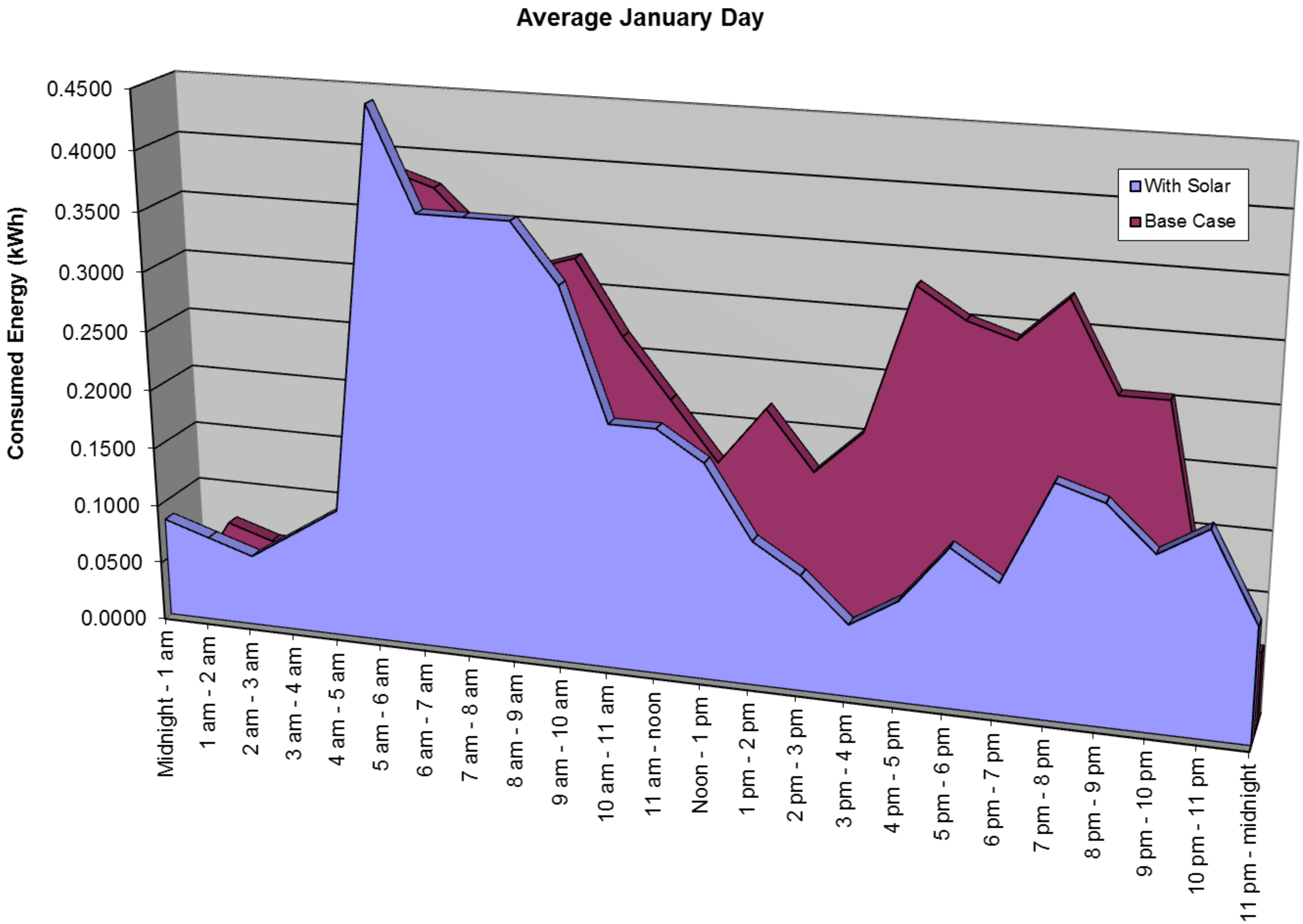

Figure 5-7. Consumed energy for an average January day.

CHAPTER 6
CONCLUSIONS

Conclusions from Experiment

The impact of solar water heating on reducing peak electrical demand has gained interest as many utility companies in the south have experienced infrequent but severe peaks during cold winter mornings. Solar water heaters, due to the inherent thermal capacitance, store energy for the times of low solar input. A review of published literature demonstrated limited success with solar water heating as a means for winter peak reduction, but the particulars of the systems and the tests as well as the transferability to other areas was not accessible. Due to this knowledge gap, the effectiveness of an ICS system was investigated. ICS was chosen because it is a modestly priced passive system included in the incentives program by JEA and Beaches Energy.

To determine the effectiveness of winter peak reduction, a test plan was developed and successfully implemented. The test system included a support structure for an ICS system, ambient and performance sensing and recording instrumentation, and the infrastructure and controls to recreate the hot water load profile of a residential home.

The data showed that the ICS system contributed approximately 44% of the energy required to meet the water heating load, thus exists the potential to reduce the winter morning household peak electrical load by greater than 10%. This energy comes nearly all from the stored thermal capacitance. This benefit to the utility companies can justify the solar installation incentives program and also combat the negative effects associated with peak demand.

Further Work

Due to the electrical resistance elements of the auxiliary water heaters, the instantaneous power requires bursts of high current with varying frequency and duration. Without a control strategy or timer to intentionally stagger the electricity draws, even with an ICS system reducing the overall electricity needs, there is still potential for high peaks. Further study and experimentation with demand side management, timers and/or other control strategies and devices open opportunity for optimizing a hybrid arrangement to maximize the effects of solar water heating on peak demand.

Based on the installation and maintenance variables that affected the experimental and modeling performance, there are opportunities to further research the effects of collector angle and orientation and how routine collector cleaning effects solar absorption.

The current solar collector sizing standards do not account for system design or overnight energy storage capacity and the effects on peak demand. There are opportunities to further research these variables, as well as other ICS systems and active systems, such as active drain back design. Based on the outcome of the further research, there are opportunities to tailor the incentives according to the reduction of winter electrical peaking.

LIST OF REFERENCES

[1] JEA Sets New Record for Winter Electric Peak. 2010; Available at: https://www.jea.com/Media/News_Releases/News_Archive/JEA_Sets_New_Record_for_Winter_Electric_Peak.aspx.

[2] R. Huber, USA Today, (2010).

[3] McMahon M. What is electricity demand? 2013; Available at: http://www.wisegeek.org/what-is-electricity-demand.htm.

[4] Richmond R, et al., American Solar Energy Society, (2003).

[5] B. Moore, (2007).

[6] T. Merrigan, D. Parker, American Council for an Energy Efficient Economy, (1990).

[7] L. Craig, Earth Techling, (2011).

[8] L. Sherwood, (2011).

[9] DOE, (1996).

[10] W. Beckman, J. Duffie, Solar Engineering of Thermal Processes, 3rd ed., John Wiley & Sons, Inc., Hoboken, New Jersey; 2006, pp. 238,498.

[11] M. Smyth, P.C. Eames, B. Norton, Renewable and Sustainable Energy Reviews, (2004).

[12] JEA's Solar Incentive Program. Available at: https://www.jea.com/Manage_My_Account/Ways_to_Save/Rebate_Programs/ShopSmart/Solar_Water_Heating.aspx.

[13] Instructions for Solar Water Heater Rebate. Available at: http://www.beachesenergy.com/documents/Rebates_Solar_Water_Heater.PDF.

[14] J. Koomey, R. Brown, Energy Analysis Department, (2002).

[15] KUA Sets Third Consecutive Winter Peak Demand Record. 2010; Available at: http://www.intelligentutility.com/article/10/01/kua-sets-third-consecutive-winter-peak-demand-record.

[16] Southern Company Sets Winter Peak Demand Record Again; Third Record in Seven Days Tops Summer Peak Demand. 2010; Available at: http://www.prnewswire.com/news-releases/southern-company-sets-winter-peak-demand-record-again-third-record-in-seven-days-tops-summer-peak-demand-81159202.html.

[17] Thermal Energy System Specialists, 1.03 (2009).

[18] C. Kettles, T. Merrigan, (1994).

[19] M. Bouchelle, D. Parker, M. Anello, (2000).

[20] D. Parker, (2002).

[21] A. Gravagne, K. Van Treuren, (2008).

[22] J. Haberl, S. Cho, (2004).

[23] C. Colon, D. Parker, (2010).

[24] SRCC, (2013).

[25] D. Parker, M. Mazzara, J. Sherwin, Florida Solar Energy Center, (1996).

[26] J. Lutz, et al., (1996).

[27] SRCC, (2008).

[28] PROGRESSIVTUBE® passive solar water heating system. Available at: http://www.thesolarenergycenter.com/page/391300215;.

[29] Sizing a new water heater. 2012; Available at: http://energy.gov/energysaver/articles/sizing-new-water-heater.

[30] Silicon Solar, Inovative Solar Solutions, (2008).

[31] Roof Slope. 2013; Available at: http://www.buyerschoiceinspections.com/Roof-Slope.

[32] American Society of Heating, Refrigerating and Air-Conditioning Engineers, (1993).

[33] U.S. Department of Energy's Office of Solar Energy Conversion National Solar Radiation Data Base 1961- 1990: Typical Meteorological Year 2 (TMY2). Available at: http://rredc.nrel.gov/solar/old_data/nsrdb/1961-1990/tmy2/.

[35] Florida Solar Energy Center, Summary Information Sheet. 1995; Available at: http://www.solar-water-heater.com/pdf/pt-40-cn.pdf.

[36] F. Incropera, et al., Introduction to Heat Transfer, 6th ed., John Wiley & Sons, Jefferson City, MO; 2011.

[37] Reflections Cleaning Services. 2013; Available at: http://www.reflections-cleaning.com/solar-panel-cleaning.htm.

BIOGRAPHICAL SKETCH

Benjamin Spencer Swanson was born in Lexington, Kentucky to Jeremy and Bethaney Swanson. In 1999, Benjamin moved to Jacksonville to pursue a Bachelor of Science degree from the University of North Florida. During his undergraduate studies Benjamin worked as a co-op for Smurfit Stone Container and was highly exposed to the thermal science aspects of mechanical engineering. Soon after graduation, Dr. James Fletcher offered Benjamin a position to help develop the JEA Clean and Renewable Energy Lab. This experience proved to be invaluable and was a springboard into a full time research engineering position and the opportunity to do funded research at UNF as a University of Florida graduate student. Benjamin graduated with his Master of Science in mechanical engineering in the fall of 2013.