MONITORING AND MODELING HOT WATER CONSUMPTION IN HOTELS FOR SOLAR THERMAL WATER HEATING SYSTEM OPTIMIZATION

A Thesis
by
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ABSTRACT

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(May 2011)

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As the prices of energy sources rise and become more volatile, renewable sources become more attractive. Solar thermal water heating technology is becoming cheaper and is currently heavily incentivized in many states in the U.S. and by the federal government. Water heating consumes one third of the energy used by the lodging industry in the U.S. Solar thermal water heating systems can be used to supply 60% or more of the required heat to hotels. However, in order to maximize a system's performance, the hot water draw profile for that particular hotel must be known. Hotel hot water consumption data is sparse and outdated. Hot water draw profiles can affect solar thermal water heating systems, but the extent to which this is true for commercial systems is not well-defined. Also, it is unclear whether or not there is an accurate way to predict hotel hot water consumption.

In this study, hot water consumption was monitored at two hotels in Boone, North Carolina. A typical hot water profile was created for each hotel, and the profiles were then used to size a solar thermal water heating system for each of them. The systems were modeled and optimized with TRNSYS 16. Then, the effect of altering the hot water draw profile on solar thermal system performance was investigated. The effect of hotel occupancy on hot water consumption was also explored.

The optimal collector tilt angle (a few degrees below latitude) and collector flow rate (1 to 1.5 gpm per square foot of collector area) are similar to the values found in literature, but it was found that the optimal flow rate decreases with increasing collector area. The optimal storage volume was found to be 3 to 4 gallons per square foot of collector area, which is roughly twice the size recommended for residential solar thermal water heating systems. The hot water draw profile was found to have little effect on a properly-sized system's life-cycle savings (2.7 to 3.8%). No correlation was found between hotel occupancy and hot water consumption.

DEDICATION

To my parents, for encouraging me to pursue my dreams, and for raising me in a stable and nurturing home

To my grandfather, Alfred, known to me as Pop, who passed away last year but will never pass away from our hearts

ACKNOWLEDGMENTS

Thanks to all four members of my thesis committee: Susan Doll, Marie Hoepfl, Brian Raichle, and Jamie Russell. They all put in many, many hours of reading, editing, discussing, and problem-solving. Dr. Raichle was very gracious in letting me work at my own pace and giving me the freedom to investigate things at will. He is a brilliant man with an unparalleled intuition of the physical world and how it operates. He is also passionate, and those two aspects of his person make him a great teacher and a pleasure to be around. Dr. Hoepfl is by far the best editor I have ever come across. She is also a first-rate educator and a good friend.

Thanks to the hotel owner (whose name will remain confidential), who allowed me to conduct research at his properties. He was interested in the project from the start, and he was always willing to aid me in my quest for data. He gave me the contact information for several of his employees and invited me to call any time.

Thanks to my parents for allowing me stay at home during my time writing, and for supporting me, both financially and lovingly, while I was mostly unemployed. Not all parents would do that.

Thanks to my brother, Michael, and all of my friends, who provided an outlet that prevented me from getting lost in the details for too long, perhaps never to return.

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CHAPTER 1

INTRODUCTION

The prices of all conventional energy sources for heating—including oil, natural gas, propane, and electricity—have been increasing rapidly over the past decade, and, with the exception perhaps of natural gas, this trend is projected to continue (Energy Information Administration [EIA], 2010b). Renewable energy sources are becoming financially viable for several reasons. One is that although systems utilizing renewable energy sources generally have a higher capital cost than fossil fuel-based systems, they do not require as many ongoing operational costs. Thus, systems powered by renewable sources can be used to hedge against rising fuel costs.

Another reason renewable energy systems are becoming more attractive is that the majority (Renewable Energy World, 2010) of state legislatures in the United States have adopted a Renewable Portfolio Standard (RPS), which mandates that a certain percentage of the total energy sold by utilities be generated by renewable sources. In order to meet these standards, many state governments have incentive programs that encourage the installation of renewable energy systems, including those that involve photovoltaic or wind power generation, solar thermal heating, biofuels, and several other energy sources. The federal government also has incentive programs in place. Tax credits, rebates, grants, and accelerated depreciation schedules can significantly reduce the capital cost of renewable energy systems, making them more competitive with fossil fuel systems. In addition to mandated incentives, renewable energy producers can often sell Renewable Energy Certificates (RECs) to utility companies, driving the cost even lower by utilizing the market.

Renewable energy installation companies are aware of these trends. They often take on commercial-scale projects and thus have a large tax liability, which means they can take full advantage of the incentives offered by the state in which they operate. Sometimes the installers can claim the rights to the RECs produced by the systems.

One renewable energy technology that is gaining traction in the United States is solar thermal water heating; solar thermal collector domestic shipments increased by an average of nine percent annually from 1999 to 2008 (EIA, 2010a). Solar domestic hot water (SDHW) systems absorb heat from the sun and transfer it to the water used for showers, cleaning, and various other tasks, reducing the amount of fossil fuel or electricity needed to heat the water. Buildings that use a large quantity of hot water each day (e.g., hotels, apartment buildings, hospitals, restaurants) could potentially benefit most from SDHW systems. In many states, SDHW system installations qualify for incentive programs, and the renewable attributes of the energy produced can often be sold as RECs to utility companies or to other third parties.

In order to minimize the simple payback and maximize the return on investment of an SDHW system, all the components—such as the collector array, water storage tank, and circulating pump— must be properly sized. The problem is that “properly sized” is not the same from project to project. The system design will be different depending on the hot water draw profile (i.e., when and how much hot water is used), local weather conditions, and the desired water temperature.

Certain buildings, such as hotels, may have certain parameters that, if known, could be used to determine a method for sizing an SDHW system and would be universal to that building type. Unfortunately, in the case of hotels this information is largely unknown. Therein lies the purpose of this study: to measure those parameters required to design optimal SDHW systems for hotels and to thereby develop a design method that incorporates trends that are universal to hotels and reduces the need to measure those parameters prior to system design. This study focuses especially on hot water consumption patterns in hotels and their effect on system design and performance. An SDHW system design method tailored specifically to hotel applications will make it simpler and less expensive for companies to install properly-sized systems. This should, in turn, reduce the cost to hotel owners.

Statement of the Problem

After a search of the available literature, it is clear that commercial hot water use and water-heating energy use data in the United States are severely lacking. Furthermore, hot water consumption varies widely among commercial buildings of different types. Only a handful of original hotel hot water consumption data exists, and these data are outdated and do not account for hotel occupancy rates (Thrasher, DeWerth, & Becker, 1990, p. 22).

In order to optimize a commercial SDHW system, an accurate hot water draw profile needs to be known. Currently, given the lack of empirical data, a hotel's hot water use must be monitored in order to gain information about the draw profile. There is no other known way to accurately estimate hot water usage. Gaining insight into the hot water consumption pattern of hotels will allow for an accurate economic optimization of a solar water heating system for a given hotel. The optimum system will be more economically feasible than a system designed based on rules of thumb and outdated data, perhaps improving the financing of the project.

Purpose of the Study

One goal of this study is to determine a non-monitoring method (i.e., a method of estimation based on predictor variables) to accurately predict hotel hot water draw profiles in order to expedite the optimization of hotel SDHW systems. It would be desirable to have a model for which the parameters are identified and well-understood. This requires an understanding of hotel hot water usage patterns and consumption issues that are particular to the lodging industry. This understanding is gained by measuring hot water usage and collecting information regarding occupancy, uses for hot water, and fuel use.

Another goal is to use the hot water draw profile data to provide selected Boone hotels with an optimized solar thermal system design along with an economic analysis of such a system.

A third goal is to determine the ideal time of day for discretionary hot water usage (hot water usage for which the time and amount of use is not determined by guests, e.g., laundry machine operation) in order to optimize hotel SDHW system performance. The shape of the discretionary portion of the hot water draw profile may significantly affect the system's performance. This study aims to ascertain the magnitude and implications of this effect.

Research Objectives

The original objectives that guided this research were as follows:

Objective 1: Determine, by measurement, the hot water draw profile for each of two hotels in Boone, North Carolina, and compare the draw profiles for each hotel, noting significant similarities and differences.

Objective 2: Gather, by survey, information about occupancy rates, hot water end uses, total water use, and fuel use in the hotels. This information will then be used to determine the portion of the hot water draw profile that is discretionary (i.e., hot water usage that can occur at a time of day other than the current one).

Objective 3: Based on the survey and measured data, develop a method to predict hotel hot water draw profiles without requiring direct monitoring of hot water consumption. Identify variables that correlate with, and can therefore predict, hot water consumption.

Objective 4: Complete an exploratory optimization, minimizing the life-cycle cost, of an SDHW system for each hotel individually. Compare the optimized system to an SDHW system sized with commonly-used, rule-of-thumb techniques not based on system-specific parameters.

As the study progressed, it became clear that a majority of the information sought via the survey instrument was unobtainable. As a result, the focus of the study, by necessity, shifted away from Objectives 2 and 3 and toward Objectives 1 and 4.

Limitations

This study only covers two hotels located in Boone, North Carolina, with data collected during a three-month period. A study determining the effects of the climate, season, and culture of different regions on hot water use patterns will need to be conducted before the findings of this study can be applied to hotels in other regions. This study also deals only with mid-priced, limited-service hotels without dining services. Thus, this study has no bearing on the relationship between hot water use and meal production. Also, because of the similarity in type of hotel, the demographics for both hotels might be similar, further limiting the generalizability of these findings. All data were collected during the summer, so the study does not account for seasonal variations in hot water consumption in this region, which experiences several months of cold winter weather. However, summer usage data is important because the need to prevent summertime overheating is one of the design constraints on establishing the solar collector array area.

Significance of the Study

The instability and overall upward trend of fossil fuel prices, along with cost incentives (e.g., government investment tax credits) and production incentives (e.g., Renewable Energy Certificate markets), increase the economic viability of alternative heating methods. In the case of water heating, SDHW systems could continue to become more commonplace. Figure 1 shows historical weekly crude oil prices in blue and historical annual solar thermal collector shipments in the United States. Based solely upon visual inspection, the two values appear to be correlated.

Figure 1. Weekly United States crude oil spot price (F.O.B.), weighted by estimated import volume (EIA, 2010d), and solar collector shipments over the last two decades (EIA, 2010a).

Propane is the primary water-heating fuel used by hotels in Boone, North Carolina. These hotels are therefore likely to be good candidates for SDHW systems because the price of propane has been increasing rapidly. In addition, all of the large hotels in Boone are franchises. If the financial benefits of an SDHW system can be established for one franchise, and fossil fuel prices continue their trajectories, it will be desirable for the parent company to install systems on several more of its properties.

This study was conducted on two hotels located in Boone. Both are mid-priced, limited-service hotels without dining services (aside from free continental breakfast). The first part of this study focuses on determining the hot water usage pattern and water-heating fuel consumption of each of the hotels. Concurrent with obtaining measured data, a survey was conducted in order to discover predictor variables that affect hot water consumption, such as daily occupancy rates, amount of laundry and any other cleaning activities, number and type of guest rooms, and water recirculation technologies.

The second part of the study focuses on running simulations using TRNSYS, a transient systems simulation program, in order to determine the parameters for an optimized SDHW system for each hotel, where "optimized" is defined as maximizing the life-cycle savings. The simulation parameters that were varied include collector array area, collector flow rate, and practical changes in hot water usage patterns. Determining an optimized system design may provide strong incentive for the hotels to adopt solar thermal technology, thereby saving money for owners and decreasing greenhouse gas emissions.

This study will be beneficial to many people in many fields. Firstly, it will benefit the hotels in Boone. In exchange for allowing the monitoring of their hotels, the owners will receive an optimized SDHW system design and an economic analysis, including the estimated payback period and return on investment. They will also learn ways they can reduce hot water consumption in their hotels.

Secondly, the study will benefit solar thermal installation companies. They will have a method to accurately predict hot water draw profiles in hotels without having to monitor hot water use for an extended period of time, if at all.

Thirdly, and more indirectly, the study has the potential to benefit hotel owners across the nation. If the hotels' optimized system designs have the potential for a short payback period in Boone, SDHW systems will become more attractive to hotel owners everywhere.

CHAPTER 2

REVIEW OF RELATED LITERATURE

Commercial Water Heating Systems

Energy Consumption

The most recent Commercial Buildings Energy Consumption Survey conducted by the Energy Information Administration (EIA) indicates that in 2003, commercial buildings in the United States used over 6.5 quadrillion BTU of energy. Of this total energy expenditure, 501 trillion BTU (7.7%) were used for water heating (EIA, 2008b). Figure 2 shows the energy consumed by various end uses in U.S. commercial buildings.

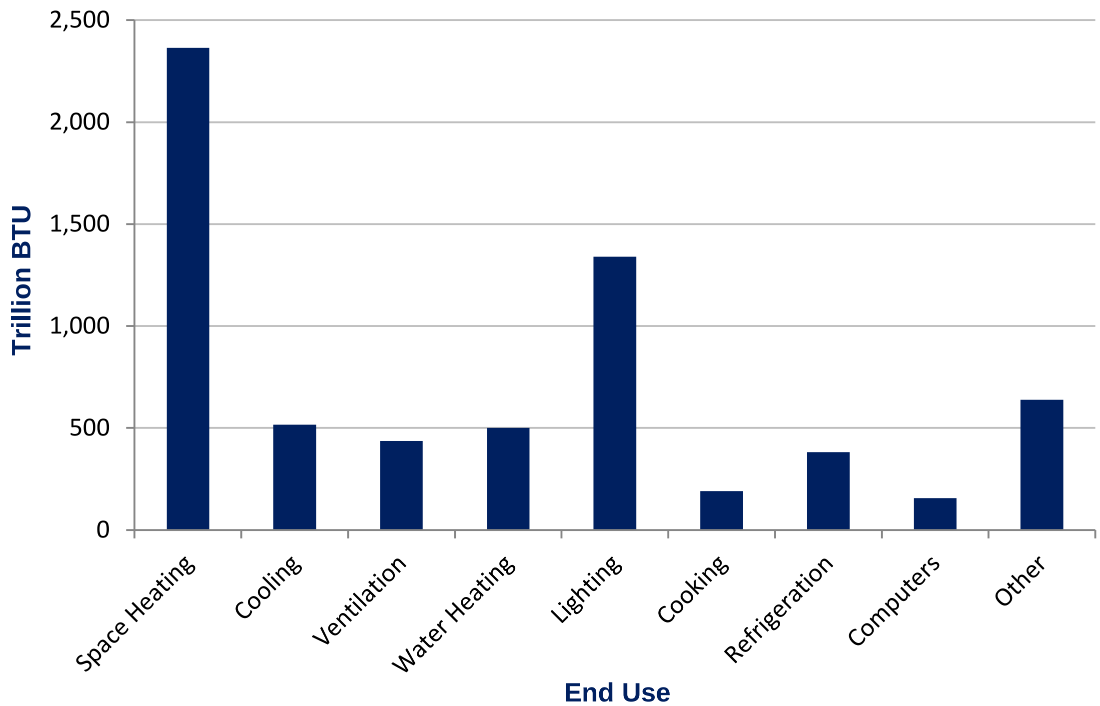

*Figure 2***.** U.S. commercial building fuel end use (EIA, 2008b).

In lodging buildings, water heating is the largest single end use for energy, making up almost 32% of total energy use, which equates to 160 trillion BTU annually in the U.S. This is 2.5% of the total energy used by all commercial buildings in the United States, including malls. Figure 3 shows the breakdown of energy use in lodging buildings by end use.

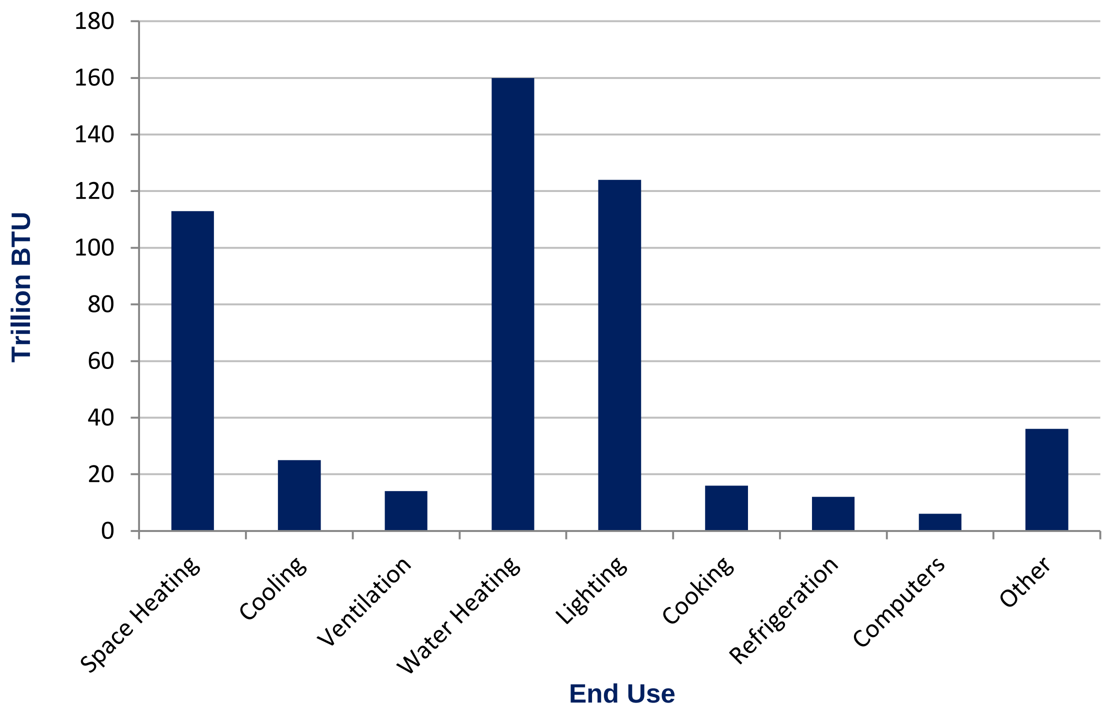

*Figure 3***.** U.S. commercial lodging building fuel end use (EIA, 2008b).

Fuel Type

Lodging buildings use a variety of fuel sources for water heating. Figure 4 shows the number of lodging buildings in the U.S. that use each of the major fuel types to heat water. The majority (52%) use natural gas as a main water heating source. The next most-used domestic hot water (DHW) energy source is electricity. Only 18,000 lodging buildings (12.7% of the 142,000 lodging buildings in the U.S.) use propane to heat water.

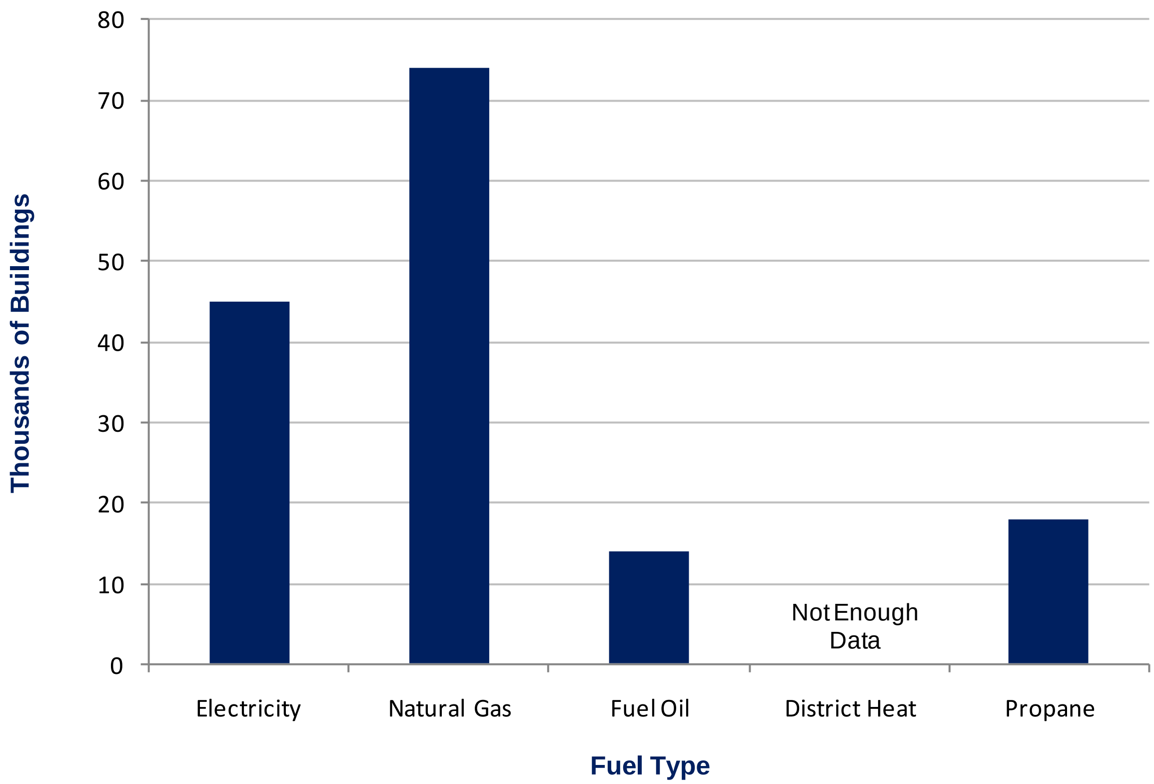

*Figure 4***.** Number of U.S. lodging buildings that use each major fuel type for water heating. Some buildings use more than one type. (EIA, 2008a).

All of the major sources of energy used to heat water in U.S. lodging buildings have become much more expensive since the 1990s. With the exception of natural gas, all of the fuel prices appear to be increasing rapidly and growing more volatile.

Natural gas. Although its price is still nearly double what it was for most of the 1990s, the price of natural gas has begun to drop because of the discovery of vast shale gas reserves and increased production stimulated by new wells being drilled in order to hold mineral rights (Saefong, 2010). At the end of 2010, natural gas prices fell below $10 per thousand cubic feet for the first time since 2004. Although the overall trend is still upward, the future of natural gas prices is uncertain. Figure 5 shows the price of natural gas sold to commercial consumers in North Carolina over the last 21 years.

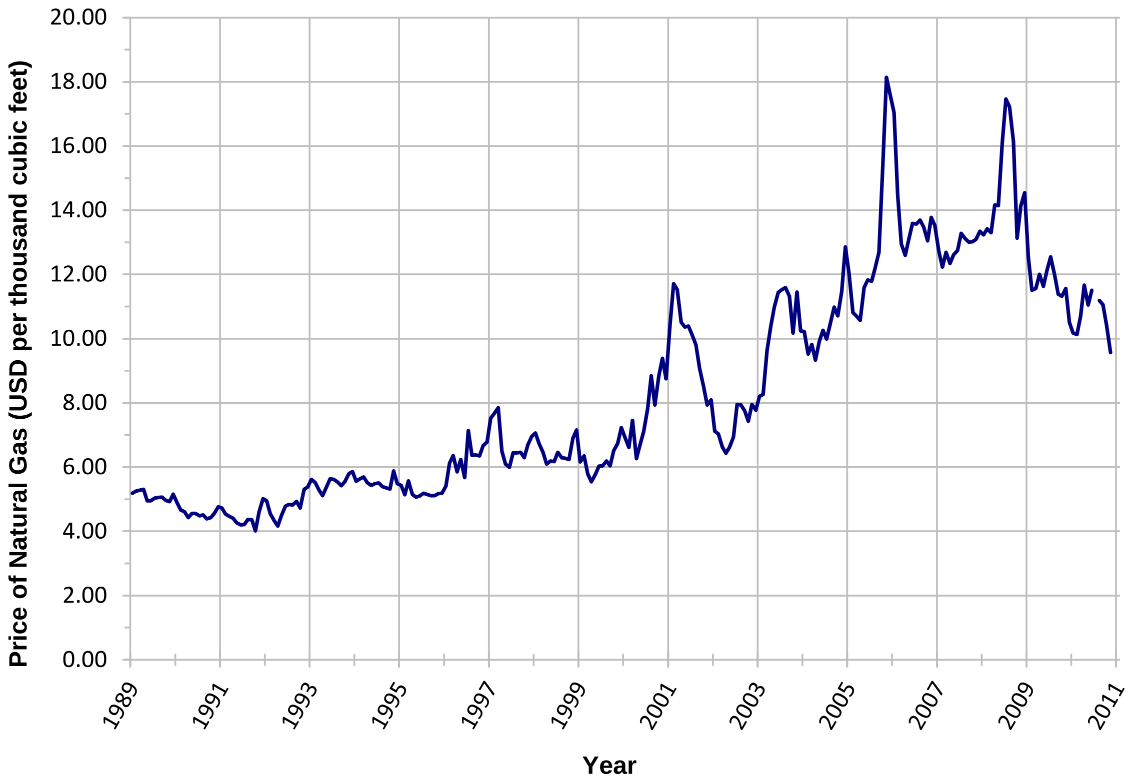

*Figure 5***.** Monthly North Carolina price of natural gas sold to commercial consumers (dollars per thousand cubic feet) from January, 1989 to November, 2010 (EIA, 2011d).

Electricity. After remaining relatively constant throughout the 1990s, the commercial price of electricity in North Carolina has been rising steadily throughout the 2000s, at an average increase of 0.18 cents/kilowatt-hour per year. As of 2009, the average price was around eight cents/kilowatt-hour. Figure 6 shows the commercial price of electricity in North Carolina from 1990 to 2009.

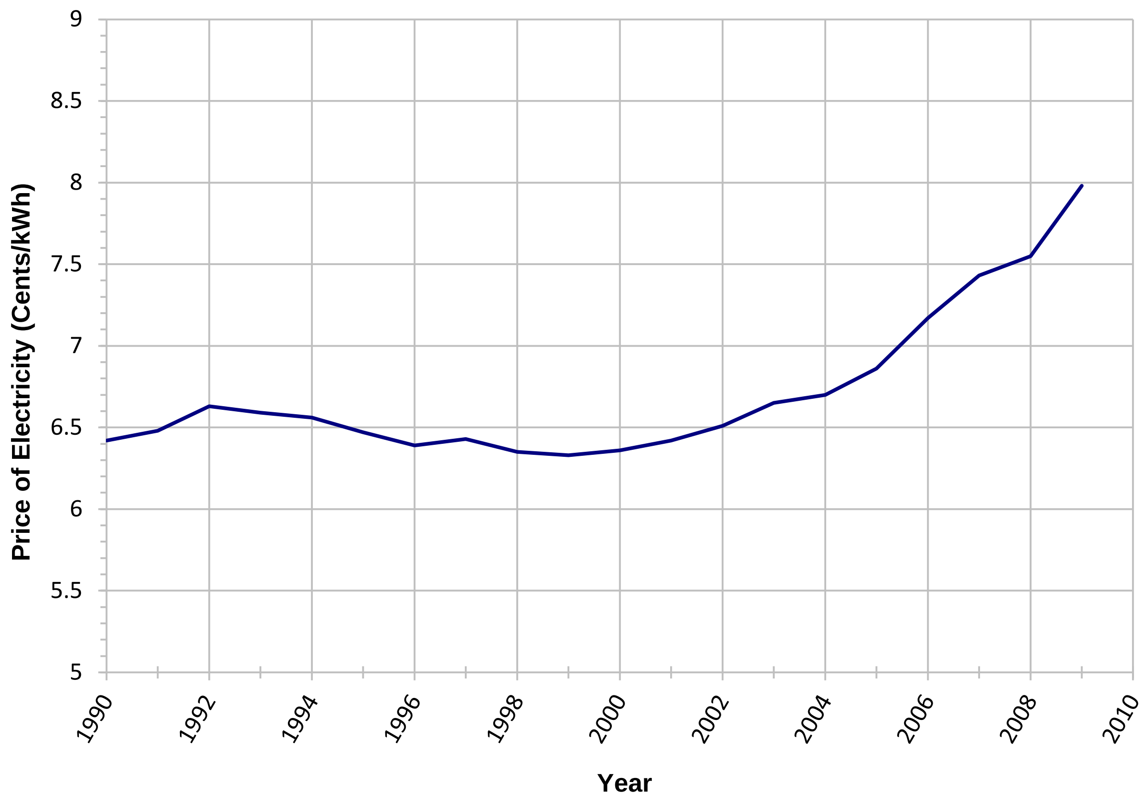

*Figure 6***.** Average yearly North Carolina commercial price of electricity (cents per kilowatt-hour) from 1990 to 2009 (EIA, 2010b).

Propane. Hotels in Boone, North Carolina are among those lodging buildings that use propane for water heating due to the rural nature of the area and lack of natural gas pipeline service. The price of propane in North Carolina has increased substantially over the last two decades. Over the last ten years, the price has also become increasingly volatile, at times fluctuating more than $1.00/gallon, or 100%, over the course of a single year. Figure 7 shows the wholesale price of propane in North Carolina for the last 20 years. It should be noted that retail propane prices are even more unstable than these wholesale prices due to artificial price variations, ever-changing delivery and tank rental fees, and the occasional attempt by companies to corner the market and engage in fraudulent price manipulation

(Department of Justice, 2007). Many propane consumers can opt to participate in a price stabilization plan, agreeing to a fixed price for a fixed period of time, but this option, when available, typically requires an up-front purchase of the propane for the entire fixed-price period.

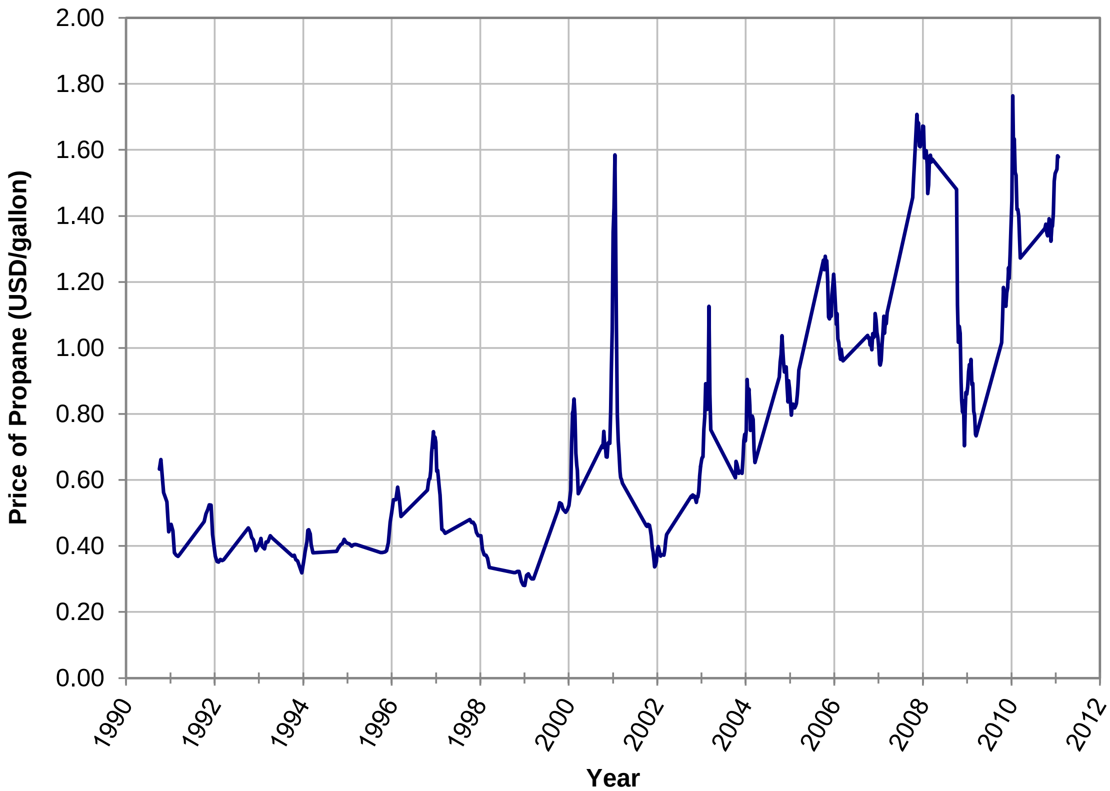

*Figure 7***.** Weekly North Carolina propane wholesale/resale prices from October 1, 1990 to January 24, 2011 (EIA, 2011f).

No. 2 heating oil. Heating oil use is more common in northeastern states. The 20-year trend for heating oil prices is very similar to that of propane. Figure 8 shows the wholesale price of No. 2 heating oil in North Carolina over the last 20 years.

*Figure 8***.** Weekly North Carolina No. 2 heating oil wholesale/resale prices from October 1, 1990 to January 31, 2011 (EIA, 2011e).

Conventional Commercial Water Heating System Design

Water heaters for commercial buildings are often sized according to system-sizing charts and calculators on the manufacturer's web site. AO Smith (AO Smith, 2009), American Water Heaters (American Water Heaters, 2009), and State Water Heaters (State Water Heaters, 2009) are three examples of prominent water heater manufacturers that have system-sizing calculators on their web sites. The calculators take into consideration site altitude, fuel type, cold water temperature, stored water set point temperature, business type, duration of the peak demand period, shower head flow rate, laundry capacity, food service water use, business type, number of rooms, persons per unit, number of service sinks and public lavatories, and miscellaneous loads. They do not require or allow input of the water usage; it is likely that they instead estimate hot water usage per person per day. The calculator used on each of these sites is the same and is designed by Avenir Software, Inc.

Buildings with long runs of pipe between the water heaters and the point of use frequently employ a hot water recirculation system. A circulation pump is used to continually (or intermittently, controlled by a thermostat) circulate hot water from the water heaters to the pipe from which water is drawn by faucets. This ensures that hot water is readily available with only a few seconds of lag time. Without a recirculation system, the pipes would eventually cool off, and users could wait a considerable amount of time for hot water, especially in a building in which the heaters are far away from some faucets. The recirculation system saves water because users do not have to let the water run while they wait for it to heat up.

Hotel Hot Water Consumption Profiles

Well-Established Residential Hot Water Draw Profiles

A hot water draw profile is the percentage of the total daily hot water flow that occurs as a function of time of day. Hot water draw profiles are well-documented for single-family residential buildings. Figure 9 (Fairey & Parker, 2004) shows several hot water draw profiles that are commonly used when sizing domestic hot water (DHW) systems for homes. Each of the profiles was determined by a separate study, but their shapes are remarkably similar.

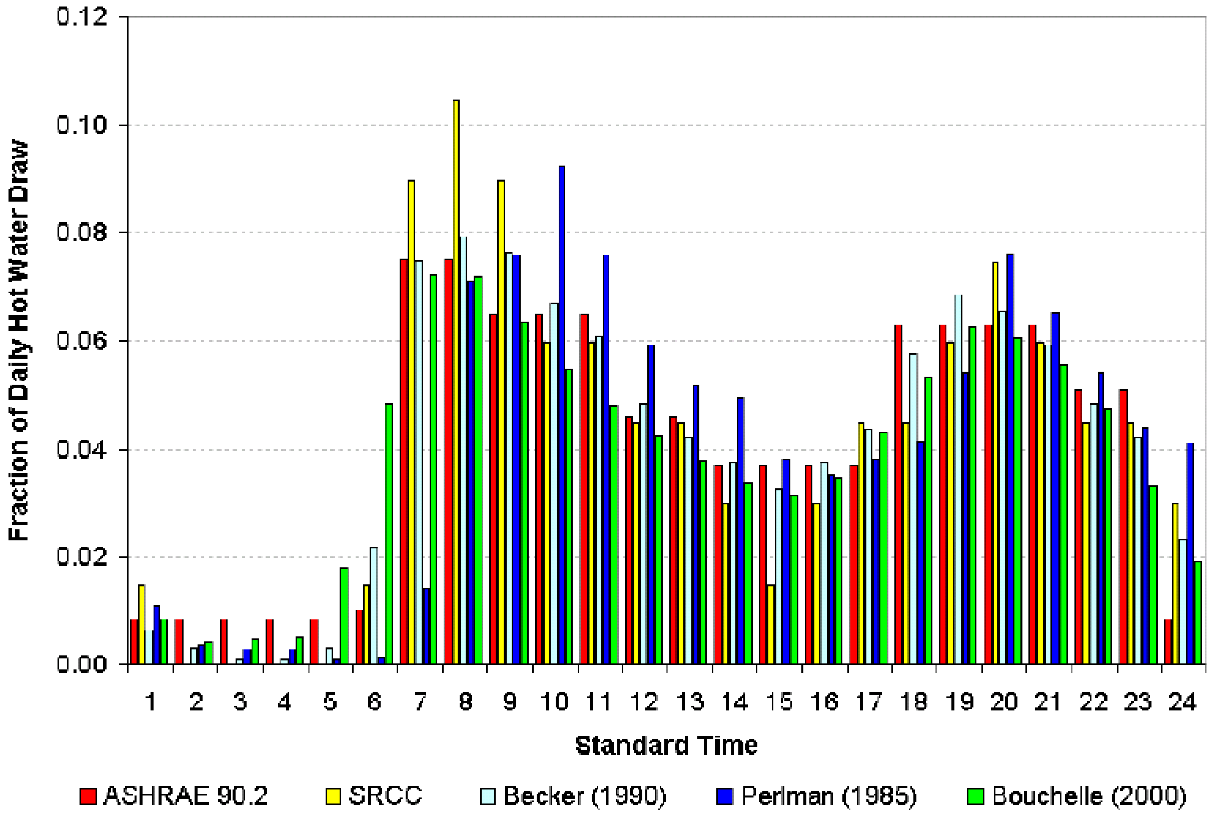

*Figure 9***.** Residential hot water draw profiles used in the United States (Fairey & Parker, 2004).

Note the twin peaks representing the predominant morning and evening hot water draw periods. There is no such standard profile for commercial hot water consumption, much less for hotels specifically. Historical data on the subject are rare, outdated, and do not reveal any strong trends (Thrasher, DeWerth, & Becker, 1990, p. 20).

Studies of U.S. Hotel Hot Water Draw Profiles and Daily Consumption

In 1990, Thrasher, DeWerth, and Becker compared existing data on hot water usage patterns in commercial establishments in the United States, including hotels and motels, for the American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE). They found 14 reports dealing with aspects of hotel and motel water heating, but only four of those contained original data: Werden & Spielvogel (1969); Department of Energy [DOE] (1981); Racine & Compillo (1986); and Carpenter & Kokko (1988). All of the hot water consumption was reported in units of gallons per day per room, with consideration given to neither the percentage of rooms occupied nor the hot water draw profile (Thrasher, DeWerth, & Becker, 1990, p. 20). Table 1 shows the average daily hot water consumption per room for each hotel in these original studies.

Table 1.
Service Hot Water Use in Hotel/Motel Guest Rooms and Laundry (Adapted From a Data Compilation Report by Thrasher, Dewerth, & Becker, 1990, p. 22)

Study	Number of Rooms in Hotel	Average Daily Gallons Per Room	Maximum Daily Gallons Per Room
Carpenter and Kokko, 1988	93	23.9	---
	350	48.8	---
	22	38.2	---
	31	22.9	---
	33	38.0	---
	74	18.9	---
AHRAE, 1987	≤ 20	20.0	35.0
	60	14.0	25.0
	≥ 100	10.0	15.0
Racine and Compillo, 1986	120	72.6	---
	250	23.0	---
	160	8.3	---
	205	6.3	---
	136	14.1	---
	72	81.3	---
	136	7.0	---
	114	2.4	---
DOE, 1981	390	13.4	---
	126	17.7	---
	209	19.0	---
	121	49.1	---
Werden and Spielvogel, 1969	63	13.5	29.5
	38	18.8	33.2
	75	13.4	19.8
	64	7.8	17.2
	54	15.1	33.0
	113	6.2	15.2
	72	12.1	23.5
	30	17.3	36.0
	44	12.8	25.4
	47	22.8	42.2
	72	8.4	18.6
	20	21.7	40.4
	50	12.6	27.7
	36	9.3	19.2

The Werden and Spielvogel study found an average of 14 gallons/room/day in a range of hotels averaging 55 rooms. The smallest hotel contained 20 rooms (22 gallons/room/day), and the largest contained 113 rooms (6 gallons/room/day). The ASHRAE standard hot water daily usage values, based on the same study, are as follows: 20 gallons/room for motels of 20 or less rooms, 14 gallons/room for motels with 20 to 60 rooms, and 10 gallons/room for motels with more than 60 rooms (Thrasher, DeWerth, & Becker, 1990, p. 22-23). These daily consumption values are not in agreement with those in the other three studies; they are much lower. This may be due to the types of hotels studied, the age of the study relative to the others, occupancy rates, services provided, or other factors.

The DOE study found an average of 28 gallons/room/day in a range of hotels averaging 212 rooms. The smallest hotel contained 121 rooms (49 gallons/room/day), and the largest contained 390 rooms (13 gallons/room/day) (Thrasher, DeWerth, & Becker, 1990, p. 22-23).

The Racine and Compillo study found an average of 26 gallons/room/day in a range of hotels averaging 149 rooms. The smallest hotel contained 72 rooms (81 gallons/room/day), and the largest hotel contained 250 rooms (23 gallons/room/day) (Thrasher, DeWerth, & Becker, 1990, p. 23).

The Carpenter and Kokko study found an average of 32 gallons/room/day in a range of hotels averaging 101 rooms. The smallest hotel contained 22 rooms (38 gallons/room/day), and the largest hotel contained 350 rooms (50 gallons/room/day). All of these hotels included an in-house restaurant (Thrasher, DeWerth, & Becker, 1990, p. 23).

None of the aforementioned studies provided hourly hot water use profiles, but the DOE study provided what the report calls a “typical” hourly profile, shown in Figure 10 (Thrasher, DeWerth, & Becker, 1990, p. 20).

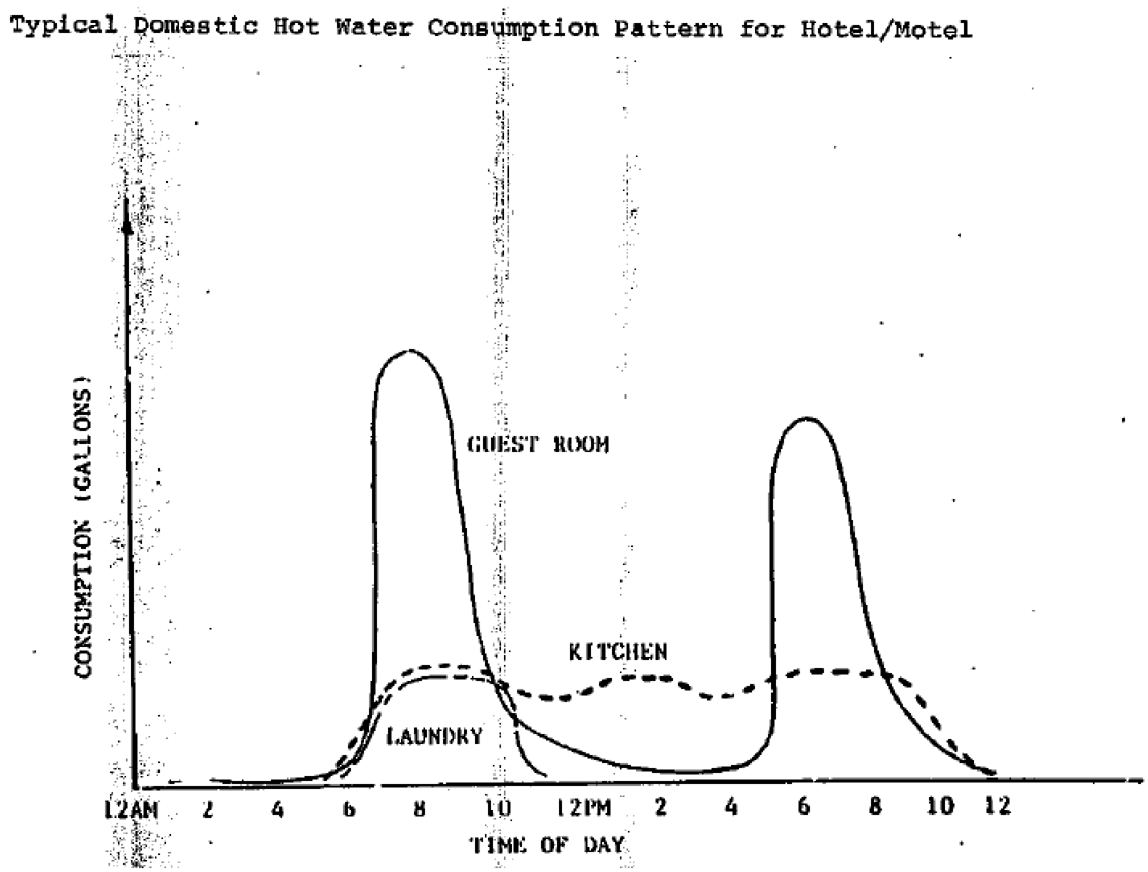

*Figure 10***.** Typical domestic hot water consumption pattern for hotel/motel, from a 1981 DOE study (as cited in Thrasher, DeWerth, & Becker, 1990, p. 24).

After looking at existing data and discovering no hotel hot water draw profiles, Thrasher and DeWerth followed up with a Phase II study. They collected hot water consumption data over a 16-month span at one full-service, 300-room hotel in a southern United States city. The hotel contained a bar, restaurant, meeting space, health club, pool, whirlpool, sauna, and laundry service. The average daily guest room hot water consumption, which was measured independently of the kitchen/laundry consumption, was 45.5 gallons/occupied room, more than four times the ASHRAE standard value for large hotels.

The average daily kitchen/laundry hot water consumption was 27.2 gallons/occupied room (Thrasher & DeWerth, 1993, pp. 21-22). Figures 11 and 12 show the hotel guest hot water usage profile for a 100%-occupied Wednesday and a 53%-occupied Sunday, respectively. It is interesting to note low values around 5:00 pm and a rising from 8:00 pm to midnight. There is a main spike of usage from 6:00 to 8:00 am on Wednesday and the same general pattern, with more eccentric use over the course of the day, on Sunday.

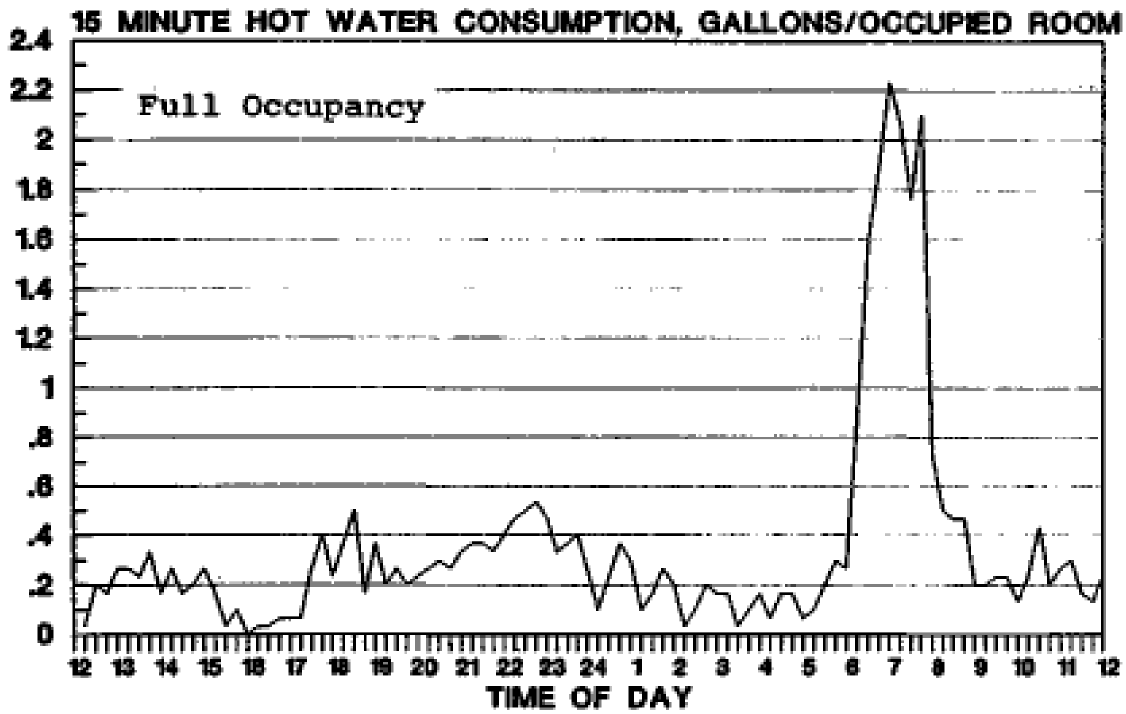

*Figure 11***.** Hotel guest hot water usage profile, noon-to-noon, on Wednesday night, December 4, 1991 to December 5, 1991, with 100% occupancy (Thrasher & DeWerth, 1993, Annex F, p. 49).

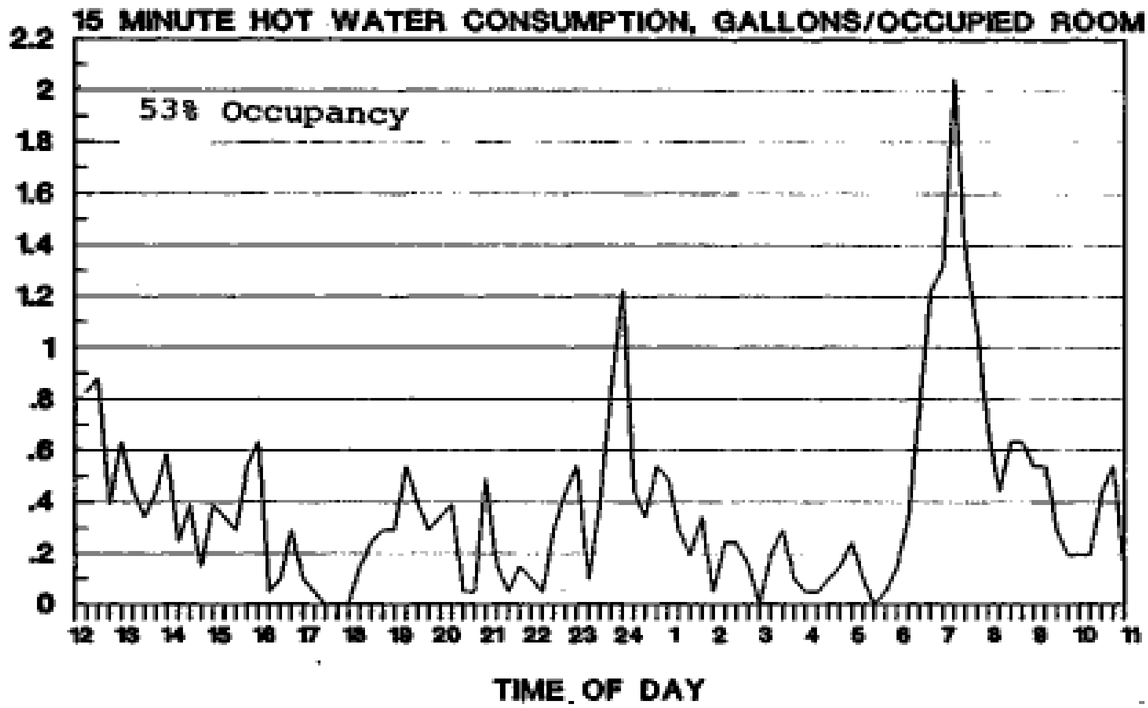

*Figure 12***.** Hotel guest hot water use profile, noon-to-noon, on Sunday night, October 27, 1991 to October 28, 1991, with 53% occupancy (Thrasher & DeWerth, 1993, Annex F, p. 50).

Non-U.S. Hotel Hot Water Draw Profiles

More recent hotel hot water consumption studies have been conducted in South Africa (Rankin & Rousseau, 2006) and Senegal (Ndoye & Sarr, 2008). In the South Africa study, hot water use data was collected from four hotels. Of those four, daily occupancy data only exist for two. A hot water draw profile for each of those two hotels was determined. This result is shown in Figure 13. Researchers conducting a study of solar water heating potential for Indian hotels used a draw profile similar to the profile resulting from the South Africa study (Pillai & Banerjee, 2007), but it is unclear how this profile was selected. The Senegal study looked at one three-star hotel in Dakar and found the hot water draw profile displayed in Figure 14.

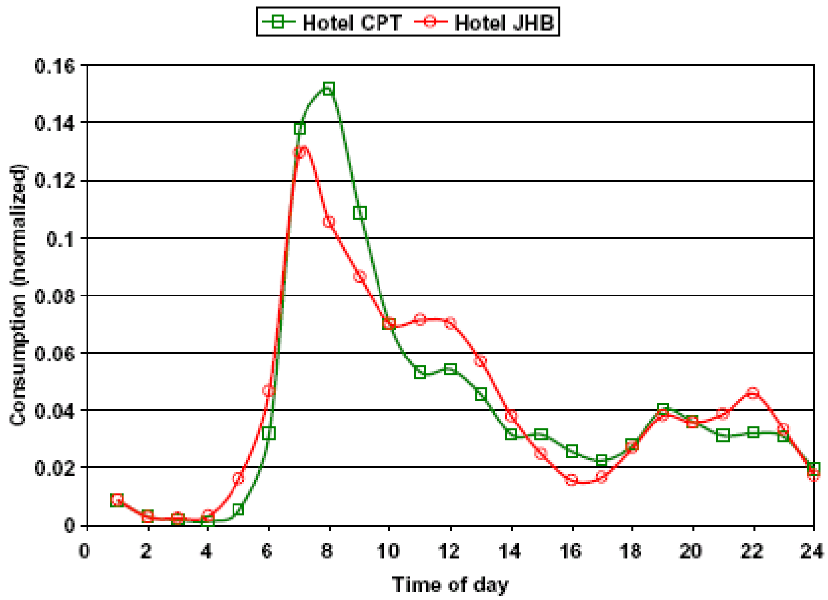

*Figure 13***.** Hot water draw profiles for two hotels in South Africa (Rankin & Rousseau, 2006, p. 693).

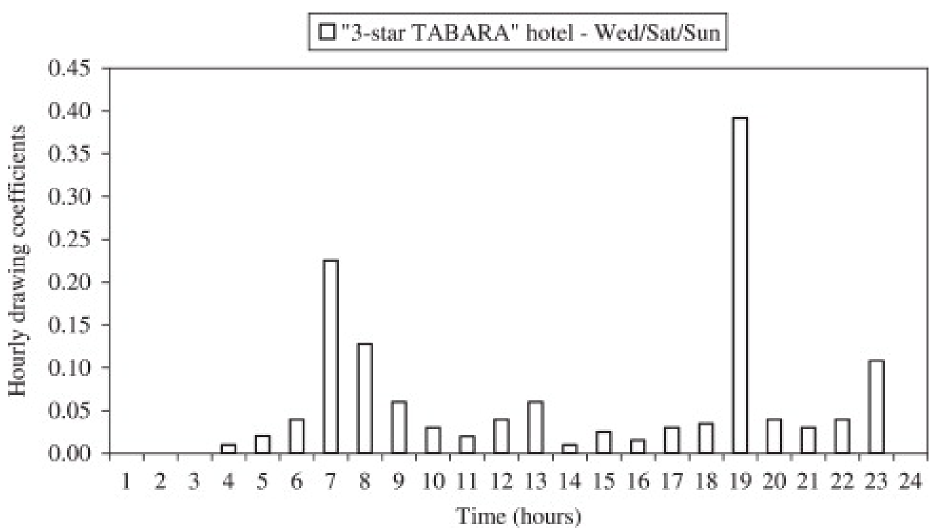

*Figure 14***.** Hot water draw profile for a three-star hotel in Senegal (Ndoye & Sarr, 2008, p. 1221).

These profiles do not exhibit the same twin peak behavior (the peaks are much taller and the durations shorter) found in U.S. residential profiles and are evidence that residential profiles cannot be applied to commercial buildings. In addition, the hotel draw profiles for the hotels in the South Africa study and the one in the Senegal study are considerably different from each other, which may imply that cultural habits have a large effect on hot water consumption. Indeed, Rankin and Rousseau summarize well a finding by Lee Schipper when they write that “American people generally use up to seven times as much water as the citizens of certain developed European countries. This indicates that data from countries with certain cultural and social norms cannot be applied to countries differing in this aspect” (Rankin & Rousseau, 2006, p. 689). Therefore, hot water draw profiles from other countries cannot be adopted for use in modeling U.S. hotel draw profiles, and the 1993 Thrasher and DeWerth draw profile is the only known U.S. hotel draw profile. Clearly, there is a need to monitor hot water consumption in U.S. hotels in order to properly size SDHW systems, or any DHW system for that matter.

Solar Water Heating Systems

SDHW System Components and Configuration

SDHW systems absorb energy radiated by the sun, convert that energy to heat, and transfer the heat either directly to a building’s potable hot water supply or to an intermediate fluid that then transfers the heat to the potable water supply. While there are many different configurations for SDHW systems, all of them have solar thermal collectors that convert the sun’s energy to heat, and most of them have water storage tanks that are larger than most conventional DHW heater tanks.

SDHW systems can be either direct or indirect systems. In a direct system, the water from the storage tank, which is also the water sent to sinks and showers, is sent directly through the collectors to gain heat. In an indirect system, a fluid (often an antifreeze mixture), which is not the water from the storage tanks, gains heat from the collectors and then transfers its heat to the stored water via a heat exchanger. SDHW systems in colder climates must be indirect systems to prevent the potable water from freezing in the collectors.

SDHW systems do not, in general, replace conventional DHW systems entirely. If a system were large enough to provide all the required heat in the winter, it would overheat in the summer, and it wouldn't be able to use all the heat absorbed in the summer, decreasing the economic value of the system. As a result, SDHW systems are typically sized to provide nearly all the required heat in the summer and around 60% of the annual required heat. The auxiliary (conventional) heater provides the remainder of the required heat.

Medium-temperature collector types. Collectors are available in a wide variety of shapes and sizes. They are generally designed to heat water to a particular temperature. Medium-temperature solar thermal collectors are designed to heat water to between 120 and 200° F (49 and 93° C), which covers the desired range for domestic water heating. The two most common types of medium-temperature solar thermal collectors used for these applications are the flat-plate collector (FPC) and the heat pipe collector (HPC). The Solar Rating and Certification Corporation (SRCC) tests and certifies solar thermal collectors and systems. Its website provides detailed information about the efficiency and performance ratings of all the collectors that it tests: http://www.solar-rating.org/ (Solar Rating, 2010).

Flat-plate collectors. Flat-plate collectors are shallow, rectangular boxes, usually between 3 and 4 m^2 in area, insulated on all sides except the top (or face), which is typically a glass cover, also called a glazing. Inside the box is a conductive, metal sheet absorber painted with a dark coating, ideally with high absorptivity and low emissivity. Radiation from the sun passes through the glazing, losing some energy along the way, and strikes the absorber sheet, which generally absorbs around 90% of the remaining energy and converts it to heat. Water or some other fluid is circulated through copper pipes that are attached to the absorber, and heat is transferred from the absorber to the fluid. FPCs are the most popular type of collector for large-scale rooftop installations because they are less expensive, easier to install, and more robust than heat pipe collectors (German Solar Energy Society, 2006).

Heat pipe collectors. Heat pipe collectors are a series of sealed copper heat pipes surrounded by glass vacuum tubes. The copper tubes are set in a dark coating and in contact with a header at one end. When the fluid at the bottom of the pipes heats up, it vaporizes and rises up the pipes to the header where it dumps its heat to the heat transfer fluid. After transferring the heat, the vapor condenses and travels back down the tubes. Because the vacuum tubes allow radiation to pass through them but also provide good thermal insulation, these collectors retain a higher efficiency than do flat-plate collectors when the temperature difference between the collector fluid and the surrounding air is increased, but this is rarely relevant for domestic water heating applications. Also, HPCs are generally more expensive and more fragile than FPCs (German Solar Energy Society, 2006).

Storage tanks. Most SDHW systems have extra thermal storage because they can only heat water while the sun is shining. Having extra storage allows the heat to be absorbed during sunny periods and stored until it is needed.

There are nearly unlimited options when it comes to selecting a tank configuration. They can vary in the number of connected tanks, height-to-width ratio, baffling at the cold water inlet or in the middle of the tank, hot water extraction location and method, heat exchanger location and type, insulation, and connections to various applications and mixing valves. A single, large storage tank can be used, or several smaller tanks can each store heat for a different application. Multiple tanks can be hooked up together in series (outlet-to-inlet) or in parallel (outlet-to-outlet) (German Solar Energy Society, 2006).

System sizing. The National Renewable Energy Laboratory (NREL) provides a rule-of-thumb guideline for sizing residential SDHW systems. It recommends a water storage volume of 1.5 gallons per square foot of collector area. The collector area, according to the guideline, should be 20 square feet for each of the first two residents and, in the Sun Belt, an additional eight square feet for every additional resident, or in the northern United States, an additional 12-14 square feet for every additional resident. This sizing technique is designed to meet 90% to 100% of a home's hot water needs during the summer (National Renewable Energy Laboratory [NREL], 2003).

For commercial and industrial SDHW systems, ASHRAE recommends using its standard hot water consumption rates and running computer programs, such as TRNSYS or f-Chart, to optimally size system components (ASHRAE, 1988).

The German Solar Energy Society provides a method for designing large-scale solar thermal systems when the total daily hot water consumption is known. To obtain a solar fraction of 0.5 (i.e., to have the SDHW system provide 50% of the required annual heat), it recommends 1.25 m^2 of collector area per 50 L of daily hot water consumption; 50 to 70 L of storage tank volume per m^2 of collector area; and 0.2 m^2 of heat exchanger surface area per m^2 of collector area, if using an immersed, plain tube heat exchanger (German Solar Energy Society, 2006).

It is not usually economically feasible for a supplemental SDHW system to fulfill 100% of the water heating demand. SDHW systems follow a law of diminishing returns (Reddy, 2007). Therefore, it is necessary to optimize the collector area, storage volume, collector tilt angle, and other variables in order to minimize the system's life-cycle cost, which happens when a balance is found between the system's size and the amount of energy the system produces.

Impact of Hot Water Draw Profiles

The rate and frequency of hot water draws from a storage tank, and subsequent flow of cold water into the tank, can affect the thermal performance of solar domestic hot water systems. One reason is that using all of the heat gained will prevent overheating of the heat transfer fluid and the storage tank. The other reason is that fewer and slower draws can help to preserve thermal stratification in the storage tank and thereby improve the overall system efficiency.

On economics. Pillai and Banerjee (2004) conducted an analysis of the impact of the draw profile on the economics of residential SDHW systems in India. They considered a "standard" profile (with a tall peak in the morning, a short peak at around 1:00pm, and a short peak at around 7:00pm) and an "average" profile (with uniform draw from 6:00am until 8:00pm, and no draw otherwise). It was determined that the standard profile minimized payback period and cost of energy saved. The authors determined that, if possible, the draw profile of a residence should have its tallest peak in the morning. However, this study only considered two profiles, and the authors did not comment on the impact of hot water draw on the storage tank's thermal stratification.

On storage tank thermal stratification. Researchers have, since as early as the 1960s and 70s (Close, 1967) (Sheridan, Bullock, & Duffie, 1967) (Gutierrez, Hincapie, Duffie, & Beckman, 1974) (Davis & Bartera, 1975) (Lavan & Thompson, 1976), been aware of the importance of including storage tank thermal stratification (separation of a fluid's hot and cold zones resulting from temperature-based density differences) in solar water heating models. The inclusion of storage fluid stratification in models is important for two distinct but related reasons. The first is that thermal stratification naturally occurs in storage tanks, especially during times of disuse, so its inclusion is necessary to accurately reflect physical reality and predict the temperature at the outlet. The second is that thermal stratification drastically improves an SDHW system's overall efficiency, so neglecting this effect will lead to underestimation of system performance and possibly under-sizing of the storage tank.

Thermal stratification improves the efficiency of SDHW systems for two main reasons. Firstly, it is beneficial for the fluid drawn from the bottom of the storage tank and circulated through the collectors to be as cold as possible because this maximizes the amount of heat that the fluid can absorb during its residence within the collectors. Secondly, it is beneficial to maximize the temperature in the top of the tank because this maximizes the amount of exergy, or usable energy, in the tank. To illustrate this concept, consider the following example. The desired outlet temperature is 110º F, and the entire tank is at a temperature lower than that, so the energy stored in the tank is unusable. However, if the top half of the tank is 125º F and the bottom is 95º F (i.e., the tank is thermally stratified), water can be extracted from the top of the tank, and some fraction of the water meets the outlet temperature requirement, so it is therefore useful.

A study by Sharp and Loehrke (1979) found that maintaining thermal stratification in a water storage tank can increase overall system performance by 5% to 15%. Another study determined that a tank with a high degree of stratification can provide 5.25% more energy per year than a fully mixed tank (Cristofari, Notton, Poggi, & Louche, 2003).

That thermal stratification can be decreased if excessive mixing is caused by high or sustained hot water flow rates (i.e., tall or wide peaks in the hot water draw profile) has been well-documented. One study found that high mixing rates during hot water draw-offs of small systems cause a substantial decrease in the performance of the systems (Knudsen, 2002). Another study found that available, deliverable stored energy is influenced by the volume of hot water draw-offs and initial tank stratification conditions. This study clearly demonstrates the relationship between high draw-off flow and deliverable energy (Shah & Furbo, 2003). Jordan and Furbo (2005) later performed a study comparing two different tank inlet devices designed to modify the cold water inlet flow rate. They concluded that thermal stratification inside the tank depends on hot water flow rate and draw-off volume, as well as initial storage temperatures. The lower-flow device was found to reduce the auxiliary energy requirement by 3% to 7%. It remains to be seen whether this effect is as pronounced in larger, commercial systems, although there is no reason to assume otherwise. If so, it would be advantageous to prevent instances of large hot water flow rates (such as the morning hot water use peak from the South Africa hotel study mentioned previously) in commercial buildings, either by adjusting the hot water draw profile or by using some sort of baffling system on the storage tank's cold water inlet.

A simulation study conducted in 2000 investigated (numerically and experimentally) the effects of tank aspect ratio, collector flow rate, and draw-off time of hot water on thermal stratification in a solar thermal system. It was concluded that, in order to maximize energy output, peak hot water draw should occur at around three hours past solar noon (the time when the sun is at its highest point) (Kerkeni, BenJemaa, Kooli, Farhat, & Belghith, 2000). Similarly, Jordan and Vajen (2001) found that the optimal draw-off time is 2:00 pm. This indicates that it may be possible to decrease the optimum size and therefore cost of a hotel solar thermal water heating system as long as the hot water draw profile peaks can be shifted toward the early afternoon. Both of these findings conflict with Pillai and Banerjee's 2004 study mentioned previously.

On system sizing. A 1996 study on solar hot water system design criteria concluded that SDHW systems optimized for hotels should have a collector array size of 0.8, 1.0, and 1.2 m^2 per guest for hot water consumption of 40, 50, and 60 liters per person, respectively. The hot water draw profile used had a large peak centered at 8:00 pm and a smaller peak centered at 8:00 am (Michaelides & Wilson, 1996). Determining a hotel's hot water draw profile can help to further optimize the collector area.

Modeling Tools

TRNSYS, a transient systems simulation computer program, has long been considered the market leader among simulation systems. It is more flexible (though more difficult to master) than user-friendly time step analysis programs like T*SOL and RETScreen, and it can model commercial scale solar thermal systems accurately. Because users can edit the computer code and enter their own mathematical models, TRNSYS can be used to simulate many types of hot water systems. For a quick feasibility study, the easy-to-use program f-Chart can be used to statically calculate monthly averages of energy and emissions savings (German Solar Energy Society, 2006). According to the TRNSYS website,

> TRNSYS (pronounced 'tran-sis'), commercially available since 1975, is a flexible tool designed to simulate the transient performance of thermal energy systems.… TRNSYS is a well respected energy simulation tool under continual development by a joint team made up of the Solar Energy Laboratory (SEL) at the University of

> Wisconsin-Madison, The Centre Scientifique et Technique du Batiment (CSTB) in Sophia Antipolis, France, Transsolar Energietechnik GmBH in Stuttgart, Germany and Thermal Energy Systems Specialists (TESS) in Madison, Wisconsin. (Thermal Energy System Specialists, 2009)

TRNSYS essentially is an environment in which the laws of thermodynamics are obeyed. It includes a library of components, each of which contains a sub-routine of Fortran code that mathematically represents that component's physical and thermal parameters as well as the equations that govern the component's thermal behavior over time. For example, a water storage tank component's code contains information describing the tank's geometry, inlet and outlet locations, heat exchanger size and properties, heat loss coefficients, and so on. As the time during a simulation progresses, the temperature of the different zones in the tank evolve according to the laws described by the equations.

When the components are linked together, each component can pass information about its properties to the other one. The program updates each component's properties at every time step, which can be set to any length of time the user chooses. For example, if the user selects a file containing hourly weather data for a location and sets the simulation time to one year with a time step to one hour, the program will update each component's properties every hour of the simulation for one year of the simulation. Of course, the program runs its calculations much faster than real time. After a simulation is run, the results can be analyzed by looking at the result files, which are created by output components. The result files can contain useful information about the temperature in a tank over time, or a system's energy production, or anything else the user wishes to know about the system or individual components.

Using TRNSYS to model SDHW systems. Solar water heating systems generally include solar thermal collectors, a storage tank, a heat exchanger (if it's an indirect system), a circulating pump, and a controller. The TRNSYS component library contains components to represent each of these parts of the solar thermal system, plus components for weather conditions and hot water usage profiles. The solar thermal collector components allow the user to input performance parameters determined by Solar Rating and Certification Corporation (SRCC) testing (Solar Energy Laboratory, 2006). One storage tank component, Type534 in TRNSYS, is particularly useful. Many aspects of the tank, including geometry, embedded heat exchangers, insulation, and whether thermal stratification is allowed, can be changed by the user or informed by other TRNSYS components to which it is linked (Thermal Energy System Specialists, n.d.).

Accuracy of TRNSYS models. The ability of TRNSYS to accurately model thermal systems has been demonstrated repeatedly, and its methods for weather and storage tank modeling have been validated. One study, from 2006, compared the accuracy of various models for computing solar irradiance on inclined surfaces. TRNSYS recommends that users choose to use the built-in 1987 Perez model (Solar Energy Laboratory, 2006). The mentioned study demonstrates that the 1987 Perez model is the best available irradiance model and is accurate to within 7.9%. (Loutzenhiser, Manz, Felsmann, Strachan, Frank, & Maxwell, 2007).

Another study, published in 2008, analyzed the effect of the number of storage tank nodes on long-term simulation accuracy. A tank node is defined as a portion of the tank's volume. If the tank in the simulation has ten nodes, the simulation divides the tank into ten different segments and performs calculations on each segment during each time step. The use of multiple nodes allows the model to take thermal stratification into consideration, because the model keeps track of each node's temperature at each time step. The study determined that, for a simulation time of one year, the calculated annual solar fraction (the ratio of solar heat to total heat demand) for a 6-node storage tank is within 0.01 of the solar fraction for a 50-node tank. The authors noted that "the solar fraction becomes less sensitive to the number of nodes…as the length of time of the simulation increases" (Arias, McMahan, & Klein, 2008, p. 248). The study also found that the simulated annual solar fraction was less sensitive to the time step than to the number of storage tank nodes.

Commercial Solar Water Heating Systems

Commercial solar water heating systems are gradually becoming more commonplace. A multitude of incentives are now available for installers and owners of systems, and there are examples of large systems from which would-be installers can learn.

Incentives. Hotels are good candidates for SDHW systems because they consistently use a lot of hot water; they often have large, flat roofs; and they use fuels that are becoming more expensive.

Cost incentives. Incentives for solar water heating include both state and federal tax credits. North Carolina offers a 35% Renewable Energy Tax Credit for buildings in the commercial and industrial sectors, with a maximum incentive of $2.5 million per installation, which is spread over five years (Database of State Incentives for Renewable Energy [DSIRE], 2007b). The federal government offers a 30% Business Energy Investment Tax Credit or a Renewable Energy Grant, each with a maximum incentive of $1,500 per 0.5 kW, or a 30% (DSIRE, 2007a). These two tax incentives can be taken in conjunction, totaling 55% of the installed cost.

Production incentives. A major utility company in North Carolina, Duke Energy Carolinas (DEC), has a REC Standard Offer program whereby it will purchase solar RECs at a price of $30/REC, where one MWh of energy production creates one REC. This amounts to around 3.5 cents per kWh of energy produced by solar (Duke Energy, 2010).

Tax incentives. Until 2012, a special Modified Accelerated Cost-Recovery System (MACRS) schedule can be used to fully depreciate the solar thermal system in the year of installation. In most cases, this will amount to another 30% of the installed cost in decreased tax liability (DSIRE, 2010).

Existing hotel SDHW systems. Several hotels are already enjoying large savings from SDHW systems. Proximity Hotel, located in Greensboro, North Carolina, recently installed a 100-panel flat-plate SDHW system. The investment is expected, with the help of state and federal tax incentives, renewable energy certificate sales, and an accelerated depreciation program, to be recovered within four or five years. The system meets 60% of the hotel's required water heat demand and saves about $16,000 per year in water heating fuel costs (Hasek, 2009).

A 20-panel flat-plate system in the Confederate Place Hotel in Kingston, Ontario, Canada is providing savings of over $10,000 per year and is expected to pay for itself after just 3.5 years. The original anticipated payback period was seven years, but rising energy costs have cut this number in half (Hasek, 2008).

The 172-collector flat-plate system at the Hyatt Regency Scottsdale Resort and Spa in Scottsdale, Arizona is set to pay for itself in three years. Local power utility company Arizona Public Service has a partnership with Hyatt Regency whereby it purchases

Renewable Energy Certificates created by the SDHW system, helping to keep the payback period short (“Novan to Install,” 2008).

These three hotel SDHW systems, each operating under a different climate type, will pay for themselves over the course of no more than five years. With so many incentives in place and propane prices on the rise, hotel SDHW systems in Boone have the potential to produce similar results.

CHAPTER 3

METHODOLOGY

Hot water temperature and flow rate were measured in two hotels in Boone, North Carolina during June and July of 2010. A slightly different instrumentation configuration was used for each hotel (one measured the flow rate including recirculation flow, and the other measured only cold water supply flow). The data were used to calculate energy use and to create hot water draw profiles. The existing systems were then modeled in TRNSYS, using the measured hot water draw profiles as inputs, and the models were validated by comparing the model's predicted energy use to actual energy use. After the models were validated, supplemental SDHW systems were modeled and then optimized for life-cycle savings. The effect of shifting discretionary (non-guest) hot water use periods on SDHW system performance was determined.

Description of the Hotel Hot Water Systems

Hotel #1

This hotel's water heating system is located on the ground floor. It consists of three pressurized 451-liter (119.2-gallon) propane-fueled water heaters, each with a maximum input rating of 199,000 BTU/hr. The temperature set point for each of the heaters is 125º F. Cold water enters all three heaters simultaneously, and hot water leaves all three heaters simultaneously. The supply and hot water pipes are all two inches in diameter. Hot water leaves the heaters and flows towards showerheads, faucets, laundry machines, and other water uses. Some of the water returns via the recirculation loop pipes and mixes with the cold supply water before it enters the heaters. A recirculation pump, governed by a thermostat set at 105º F, sends hot water throughout the hotel via the hot water pipes so that guests do not experience a delay in hot water availability.

Hotel #2

This hotel's water heating system is the same as Hotel #1's system, except that the temperature set point for the water heaters is 128º F.

Data Collection

Hotel #1

Sensors included three 10-kilohm thermistors, clamped on the outside of the pipe and beneath insulative foam, for temperature readings at three locations on the water feed and circulation pipes. A clamp-on ultrasonic flow meter (Time Delta-C Ultrasonic Flowmeter, with FSV transmitter, FLD22 detector, and FLY signal cable, manufactured by Fuji Electronic Systems Co.) was used to measure water flow into the hot water storage tanks. These four sensors were logged with an HOBO Microstation data logger. Measurements were made once per second, and every minute the average of the previous 60 measurements was recorded by the logger.

Figure 15 shows a diagram of the measurement locations on the hot water system at Hotel #1. T_out is the water heater tank outlet temperature, T_in is the tank inlet temperature, T_c is the cold supply water temperature, and m_in is the tank array inlet flow rate (the confluence of cold water flow for tank replenishment and recirculation water flow).

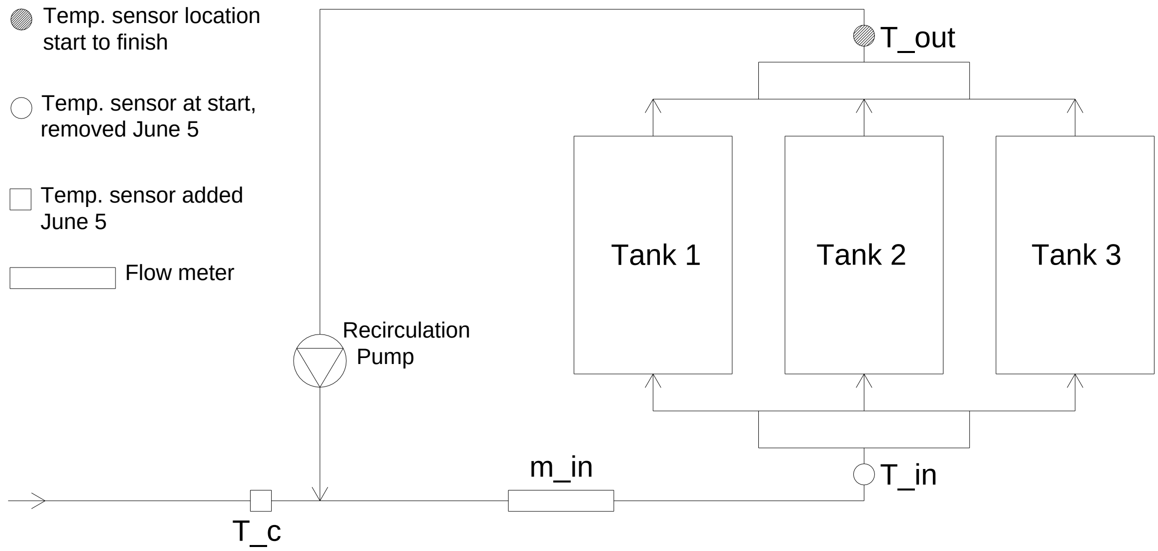

*Figure 15***.** Hotel #1 sensor location diagram.

The sensors for Hotel #1 began logging June 2 at 4:25pm. The flow meter was measuring the tank inlet flow rate (m_in), and the temperature sensors were measuring T_in, T_out, and the ambient air temperature. At 6:50 pm on June 5, the sensor measuring T_in was moved and began measuring T_c instead, in order to get a true reading of the cold supply water temperature. Data collection at Hotel #1 ended at 1:15 pm on June 17.

Hotel #2

Sensors included three 10-kilohm thermistors, clamped on the outside of the pipe and beneath insulative foam, for temperature readings at three locations on the water feed and circulation pipes. A clamp-on ultrasonic flow meter (Time Delta-C Ultrasonic Flowmeter, with FSV transmitter, FLD22 detector, and FLY signal cable, manufactured by Fuji Electronic Systems Co.) was used to measure water flow into the hot water storage tanks. These four sensors were logged with an HOBO Microstation data logger. The data were recorded once per minute.

Figure 16 shows a diagram of the sensor locations at Hotel #2. T_out is the water heater tank outlet temperature, T_in is the tank inlet temperature, T_c is the cold supply water temperature, T_r is the recirculation return water temperature, and m_c is the cold supply water flow rate.

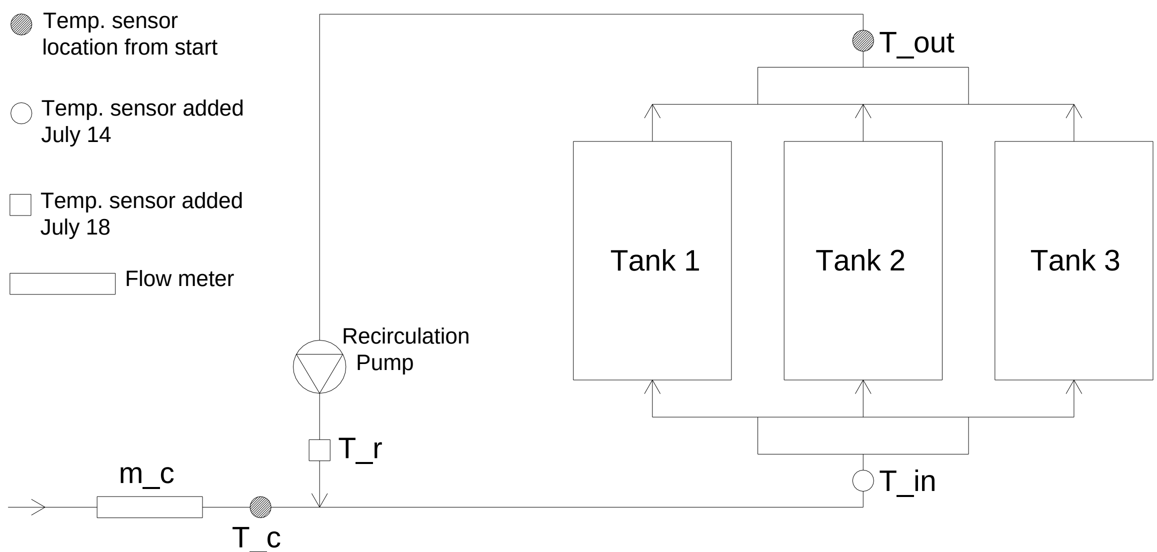

*Figure 16***.** Hotel #2 sensor location diagram.

The sensors for Hotel #2 began logging on July 5 at 5:45 pm. At this time, the flow meter was measuring the flow rate of the cold supply water (m_c), and temperature sensors were measuring T_c, T_out, and the ambient air temperature.

At 5:15 pm on July 14, the ambient air temperature sensor was moved and began measuring T_in. Thus, there were temperature sensors at T_c, T_out, and T_in.

At 10:40 pm on July 18, an additional temperature sensor was added to measure T_r, and an ammeter was added to measure the current going to the recirculation pump to determine when it was on. From that date forward, all of the temperatures shown in Figure 16 were logged.

The main data collection period for Hotel #2 ended at 6:45 pm on July 29. Then the flow meter was moved to a section of pipe between the recirculation return and the tank inlet so that the combined flow of the cold supply and the recirculation could be measured. The time between 2:00 am and 4:00 am was used to measure the flow rate when the only flow in the pipe was due to the recirculation pump (i.e., no hot water was being used by guests), because the recirculation return pipe configuration made direct flow measurement unfeasible. All data collection at Hotel #2 concluded at noon on July 30.

Survey Instrument

A questionnaire was given to a contact person at Hotel #1 and Hotel #2. The questionnaire asked for general information about the size and capacity of the hotel; laundry cycles and amounts; details about kitchen area use; the number and size of hot tubs, including so-called garden tubs in rooms; details of the current water heating system; occupancy rates; and utility costs. The full set of questions can be found in Appendix A. The only information actually received via the questionnaire was daily occupancy data.

Data Analysis

The measured temperature and flow rate data were analyzed to determine the hot water consumption and the hot water energy consumption at each of the two hotels. The measured hot water consumption data was used to create the domestic hot water draw profiles. A composite hot water draw profile was created for each hotel. The profiles were created by taking data from all the days and averaging the flow rate, in units of gallons per minute, over each ten-minute period of the day. The correlation between hot water consumption and occupancy was examined.

TRNSYS Modeling

Description of the Model

The TRNSYS model for this study contains two distinct parts: the existing DHW system, and the SDHW system. The SDHW system can be turned off at any time in order to simulate only the existing DHW system. The DHW system includes water heaters with the same volume and heating capacity as the actual heaters, although for simplicity the capacities of the three individual heaters have been combined into one larger heater.

There are two main inputs that drive the simulation: the weather file and the hot water draw profile. The weather file is a Typical Meteorological Year (TMY2) data file that represents hourly weather conditions in a typical year in Bristol, Tennessee, which is approximately 60 miles from Boone. Weather-wise, data from Bristol can be considered the most similar to Boone, which does not have its own TMY2 file. The hot water draw profile is the composite hot water draw profile that can be found in the "Results" chapter of this study.

The SDHW systems that were modeled include a collector array, a storage tank with an immersed heat exchanger, a circulation pump, a differential controller, and two sections of pipe. See Appendix B for the TRNSYS model input file, which lists all of the components and parameters used, and associated storage tank text files.

Two different models were created, one for each hotel. They are nearly identical, with the only differences being the existing DHW system parameters and the hot water draw profile.

Model Validation

The model was validated by first modeling the existing DHW system, with the measured hot water draw profile as an input, and comparing the predicted energy usage to the measured energy usage. Because the boiler heat loss coefficient and efficiency are unknown for the existing systems, the model's boiler efficiency and insulation (heat loss) parameters were adjusted until the model predicted the energy usage to within 2% of the actual weekly energy usage.

SDHW System Optimization

In this study, the optimized system is defined as "the system configuration with the highest life-cycle savings that does not allow the storage tank to reach over 190º F." The parameters varied during the optimization were collector tilt angle, collector flow rate to collector area ratio, storage tank volume to collector area ratio, collector area, and hot water draw profile. Each simulation estimates the annual energy that can be expected to be produced by the system in a typical year in Boone.

With the measured composite hot water draw profile, a storage volume of 2000 gallons, a collector flow rate to collector area ratio of 0.0467 gpm/ft^2 (2.5 gpm per collector), and a collector area of 599.52 ft^2, the collector tilt angle was varied from 15 to 50 degrees off of horizontal. The tilt angle that produced the most life-cycle savings is the optimal tilt angle. The process was then repeated with a collector area of 899.28 ft^2.

Next, using the measured composite hot water draw profile, the optimal collector tilt angle, a storage volume of 2000 gallons, and collector areas ranging from 224.82 to 1648.68 ft^2, the collector flow rate to collector area ratio was varied from 0.00667 to 0.0133 gpm per ft^2, which is about 0.25 to 5 gpm per collector. The optimal flow rate to collector area was found. Then, the process was repeated with a storage volume of 4000 gallons and collector areas ranging from 449.64 to 1648.68 ft^2.

Next, using the measured composite hot water draw profile, the optimal collector tilt angle, the optimal flow rate to collector area ratio, and collector areas ranging from 299.76 to 1648.68 ft^2, the storage volume to collector area was varied from 0.5 to 6 gallons/ft^2. The optimal storage volume to collector area ratio was found.

Finally, using the optimal collector tilt angle, flow rate to collector area ratio, and storage volume to collector area ratio, the optimal collector area was found for the measured hot water draw profile and four draw profiles created by shifting the time of the discretionary hot water draw. Life-cycle savings for systems with the optimized collector area for each draw profile were compared in order to determine the optimal draw profile.

For each simulation, recorded outputs were annual heat produced, annual solar fraction, percentage of hours the storage tank temperature was over 190º F during a year, hours of pump operating time per year, storage tank outlet temperature, and auxiliary tank outlet temperature. Derived outputs—those calculated after simulating each configuration—

were RECs generated annually, offset cost of propane, system life-cycle savings, and simple payback period.

Economic Analysis

The simulated annual solar energy production was used to calculate the number of RECs produced and the amount of propane saved annually. This information was used to perform a life-cycle cost analysis of the SDHW system and calculate the simple payback period and annualized life-cycle savings (ALCS) for the optimized systems.

The economic inputs are as follows:

- System lifespan: 20 years. This is a conservative estimate. The only moving parts in the systems are the circulation pumps, the maintenance costs of which are accounted for by the annual system operation and maintenance cost.
- Operation and maintenance cost: 3% of the total installed cost (Russo & Chvala, 2010), plus inflation, annually.
- Price of propane: determined by linearly approximating the North Carolina residential price (EIA, 2011f) from 1990 through 2010 and extending the line through 2030.
- Inflation: 2.99%. This is the 2010 fourth quarter annualized Consumer Price Index (CPI), not including food and energy, from the US Bureau of Labor Statistics (US Bureau of Labor Statistics, 2011).
- Net present value: cost / (1 + inflation) ^ year.
- Federal tax credit: 30% (DSIRE, 2007a).
- State tax credit: 35%, to be taken over the first five years of operation in equal installments (DSIRE, 2007a).

- Depreciation: Modified Accelerated Cash-Recovery Schedule (MACRS), plus 100%bonus depreciation as allowed by *The Tax Relief, Unemployment Insurance Reauthorization, and Job Creation Act of 2010 (H.R. 4853)* (DSIRE, 2010).
- Corporate income tax rate: 35%, used in the calculation of the MACRS deduction (Department of the Treasury, 2010).
- Propane water heater efficiency: 95%
- Heat content of propane: 3.836 million BTU per barrel (EIA, 2011c)
- Price of RECs: based on Duke Energy's pricing scheme in North Carolina (see Table 2). The REC prices beyond 2025 were estimated by increasing the price by 2.5% each year, as is the case from 2011 to 2025.

Table 2.
Duke Energy REC Price Schedule (Duke Energy, 2010)

RECs Class Year	General RECs Price	Solar RECs Price
2011	$6.00	$30.00
2012	$6.15	$30.75
2013	$6.30	$31.52
2014	$6.46	$32.31
2015	$6.62	$33.11
2016	$6.79	$33.94
2017	$6.96	$34.79
2018	$7.13	$35.66
2019	$7.31	$36.55
2020	$7.49	$37.47
2021	$7.68	$38.40
2022	$7.87	$39.36
2023	$8.07	$40.35
2024	$8.27	$41.36
2025	$8.48	$42.39

- Cost per installed square foot of collector area: $105 (Russo & Chvala, 2010). This cost includes most of the system equipment, such as the collectors, pump, pipes, controller, and hardware, as well as costs associated with the installation of the system, such as labor.
- Storage tank cost per gallon: tank cost (USD/gallon) = 204.84 * gallons ^ -0.576. This equation was arrived at by averaging the retail prices of storage tanks of sizes ranging from 30 gallons to 120 gallons from different tank retailers. Figures 17 and 18 show the estimates given by this equation as well as those used by Kulkarni et al., who in a recent study estimated the storage tank cost as 84.2 USD/m^2 of tank surface area, which turns out to be a much lower estimate than what is used in this study (Kulkarni, Kedare, & Bandyopadhyay, 2007). Figures 17 and 18 show these estimates as a function of tank volume.

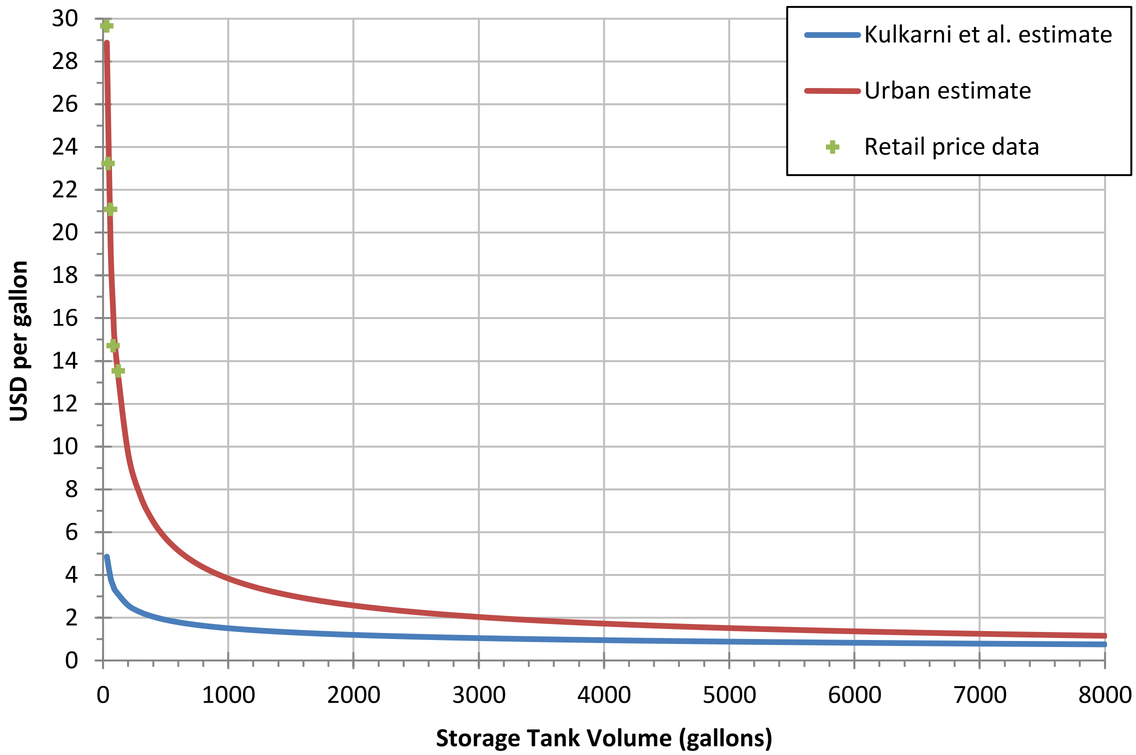

*Figure 17***.** Estimate of storage tank cost (USD per gal) as a function of tank volume (gal).

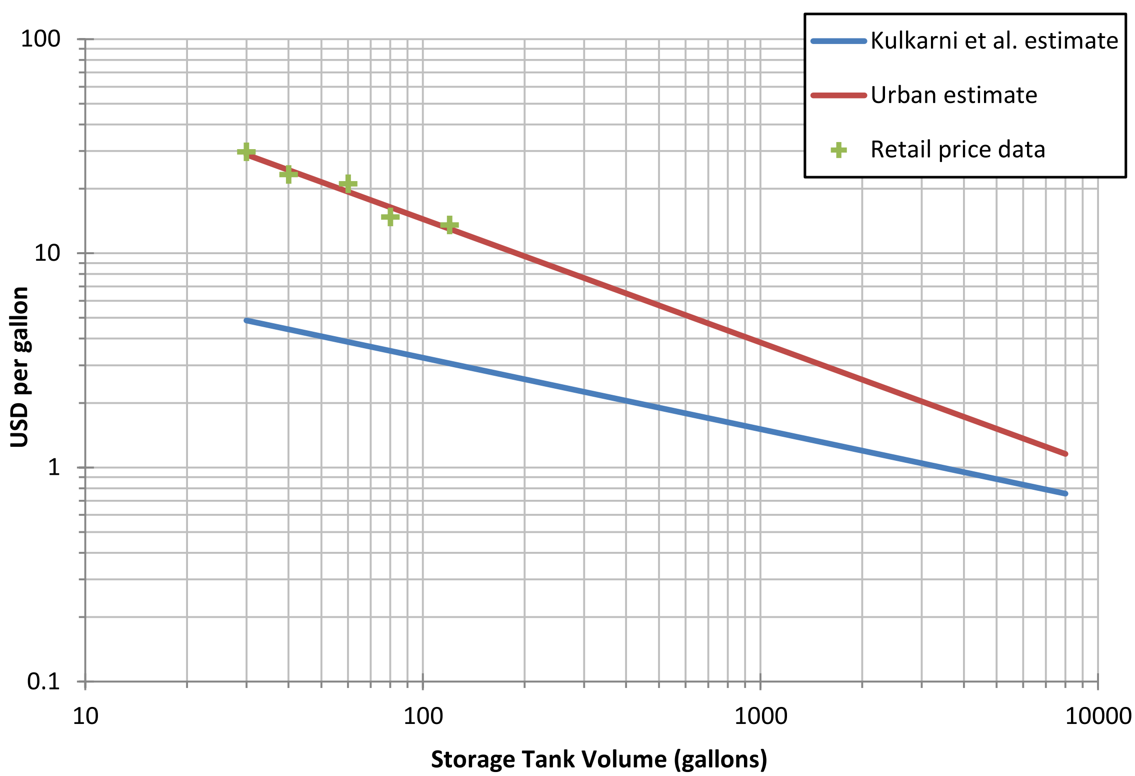

*Figure 18***.** Estimate of storage tank cost (USD per gal) as a function of tank volume (gal), plotted on logarithmic axes.

CHAPTER 4

RESULTS

Hot Water Draw Profiles

The hot water flow rates at Hotel #1 and Hotel #2 were recorded for 14 days and 15 days, respectively. Hot water draw profiles were created by averaging, in ten-minute intervals, the measured flow rates for the same time of day for each day of the testing. For each hotel, a general profile is presented, as well as a weekday profile and a weekend profile. The weekday profiles were created by averaging the flow rates from 12:00 am Monday through 12:00 am Friday, and the weekend profiles were created by averaging the flow rates from 12:00 am Friday through 12:00 am Monday. For clarity, all graphs related to Hotel #1 are colored red, and graphs related to Hotel #2 are colored blue.

Hotel #1

Consumption including recirculation flow. The flow meter at Hotel #1 measured the flow rate of the water entering the hot water heaters. It includes the flow of the recirculation loop. Figure 19 shows the general hot water profile for Hotel #1. The recirculation loop flow explains the flow during the early-morning hours. The two biggest peaks are caused mostly by showers. The flow in the hours between the two peaks is mostly caused by laundry machine usage. The total hot water consumption for the test period averaged 1964 gallons per day.

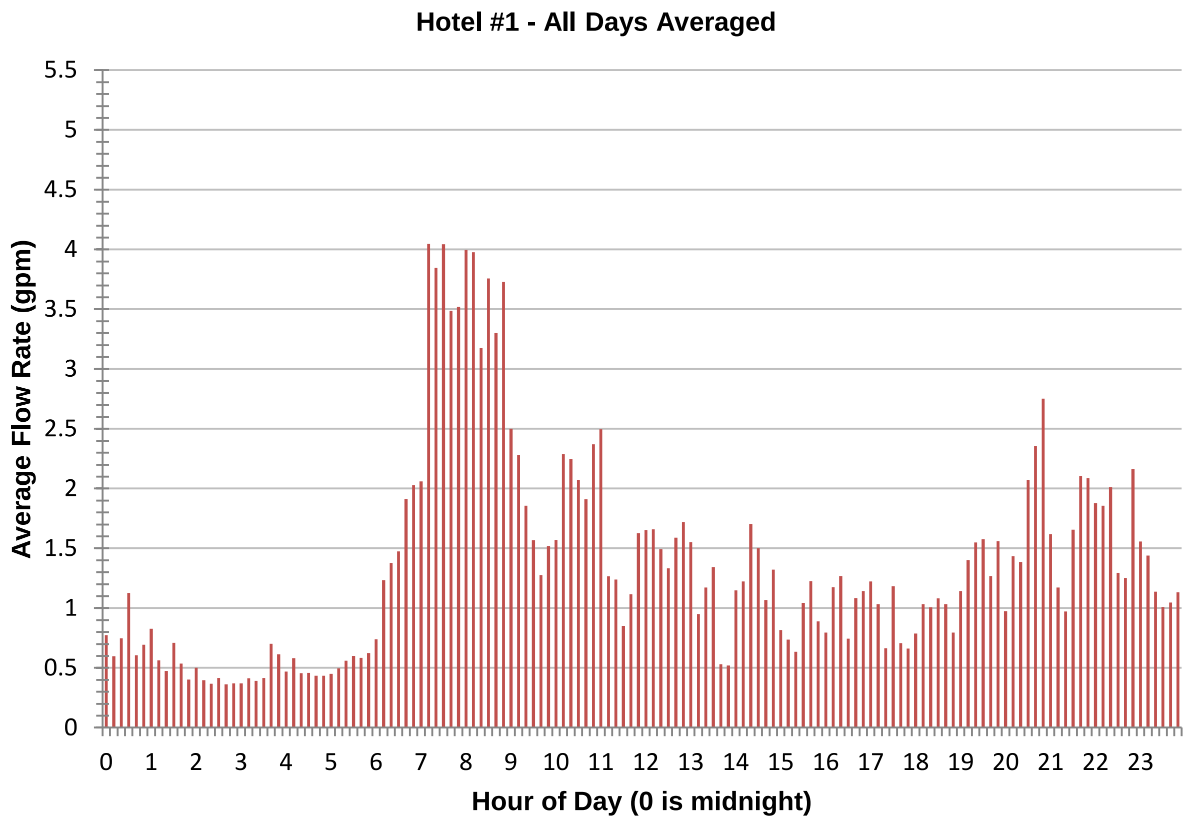

*Figure 19***.** Hot water draw profile for Hotel #1: average for all days.

Figures 20 and 21 show the profile for the average weekday and average weekend day, respectively, at Hotel #1. Weekdays averaged 1749 gallons per day of hot water use, and weekend days averaged 2250 gallons.

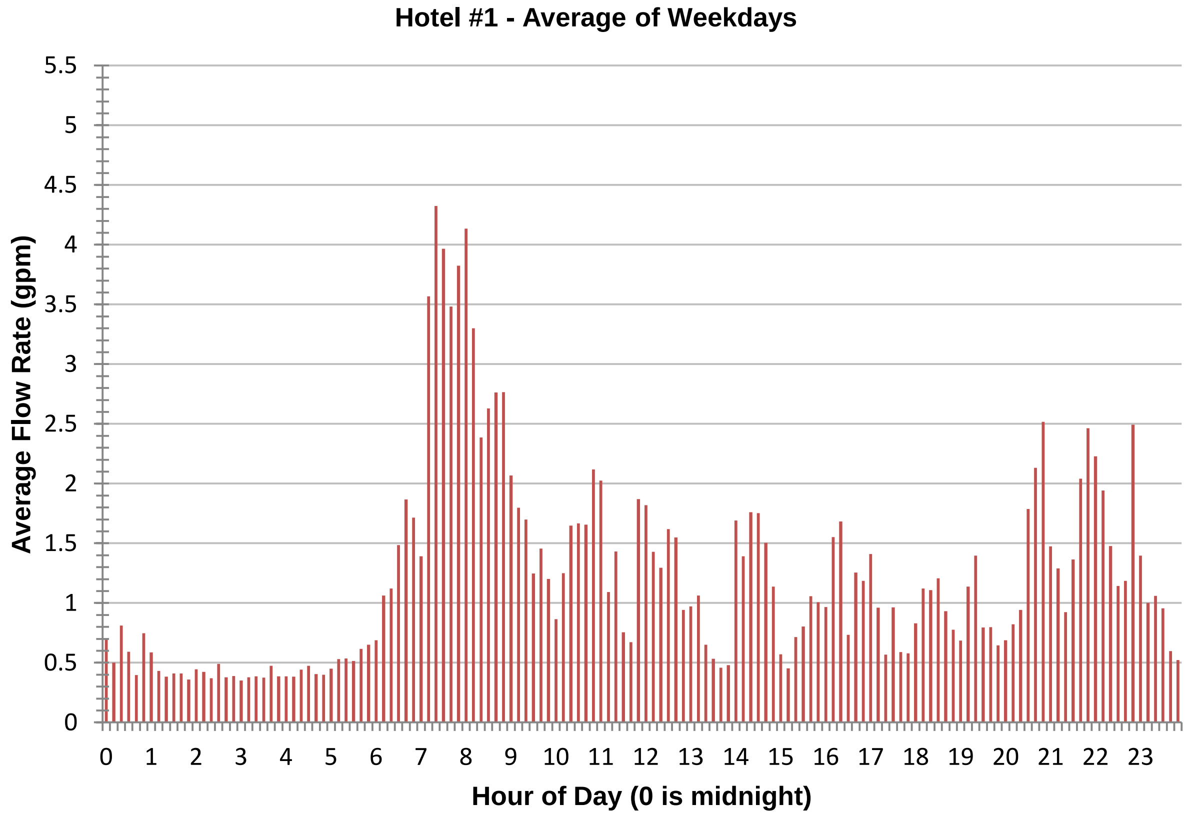

*Figure 20***.** Hot water draw profile for Hotel #1: average for weekdays.

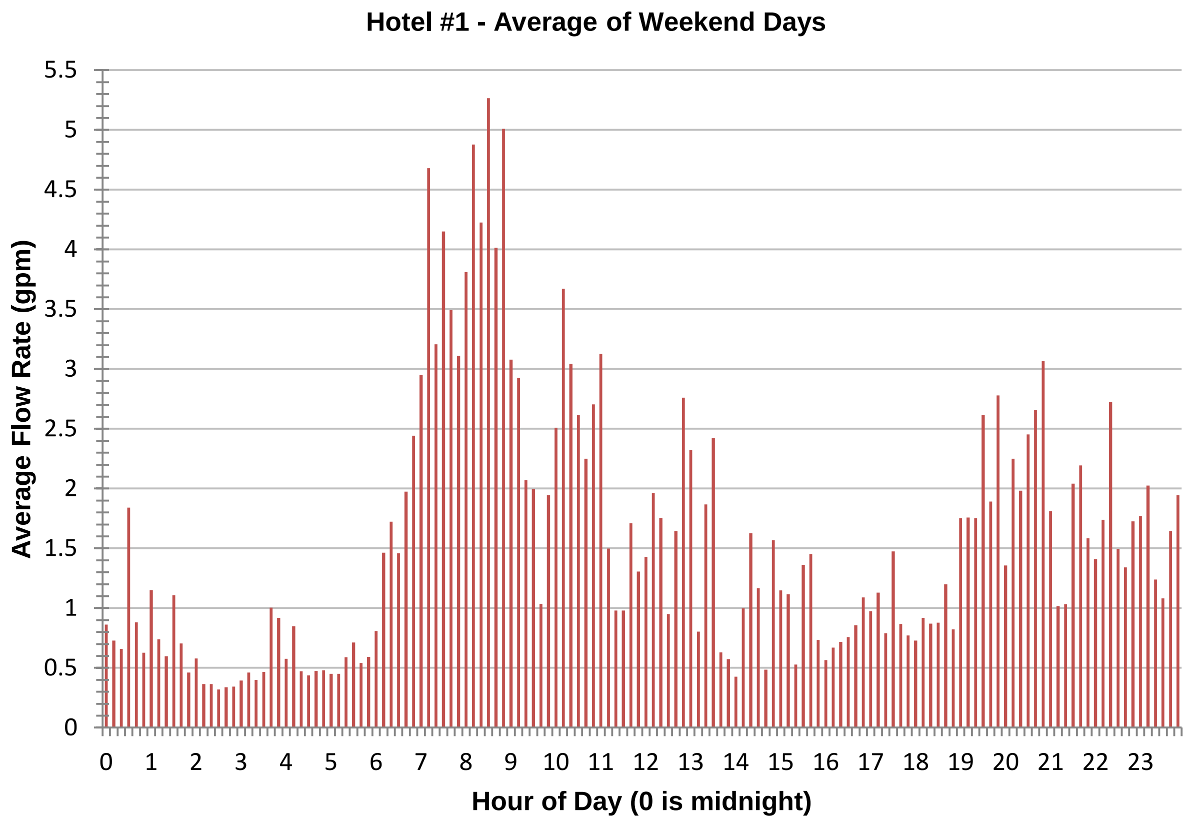

*Figure 21***.** Hot water draw profile for Hotel #1: average for weekend days.

Compared with the weekend profile, the weekday profile is characterized by tighter shower peaks, less sporadic off-peak usage, and more regular laundry usage. The main morning shower peak is about an hour earlier on weekdays. Also, the weekend profile appears to have a secondary morning shower peak, though the laundry peaks make it difficult to distinguish.

Consumption excluding recirculation flow. The temperature of the water entering the water heaters was measured for the first 73 hours of data collection at Hotel #1. This allows a calculation of the cold water flow rate to be made during that time. The two flow streams, cold water flow (m_c) and recirculation flow (m_r), combine to make up the tank inlet flow (m_{in}). By the law of conservation of mass,

$$m_c + m_r = m_{in} \tag{1}$$

By the law of conservation of energy,

$$m_c\, c\, T_c + m_r\, c\, T_r = m_{in}\, c\, T_{in} \tag{2}$$

where T_c is the cold water temperature, T_r is the recirculation water temperature, and T_{in} is the tank inlet temperature. The heat capacity of water is represented by c. Combining Equations 1 and 2 yields:

$$m_r = \frac{m_{in}\, T_{in} - m_{in}\, T_c}{T_r - T_c} \tag{3}$$

After the first 73 hours of data collection, the cold water temperature, rather than the tank inlet temperature, was measured. The average cold water temperature was used for T_c in equation 3, allowing for calculation of m_r during the first 73 hours.

The recirculation pump is controlled by a thermostat set to 105 °F. The recirculation pump was assumed to be on for all minutes during which the following conditions were met:

$$T_{in} > \overline{T}_c + 2\ standard\ deviations$$

$$m_{in} \geq m_r\ (as\ calculated\ by\ Equation\ 3)$$

$$m_{in} > 0.6\ gpm\ (the\ lowest\ flow\ rate\ measured\ between\ 2{:}00\ am\ and\ 4{:}00\ am)$$

For all times during which the recirculation pump was assumed to be on, the cold water flow rate was assumed to be:

$$m_c = m_{in} - m_r\ (as\ calculated\ by\ Equation\ 3)$$

For all times during which the recirculation pump was assumed to be off, the cold water flow rate was assumed to be:

$$m_c = m_{in}$$

Figures 22 and 23 show the measured inlet flow rate and the calculated cold water flow rate.

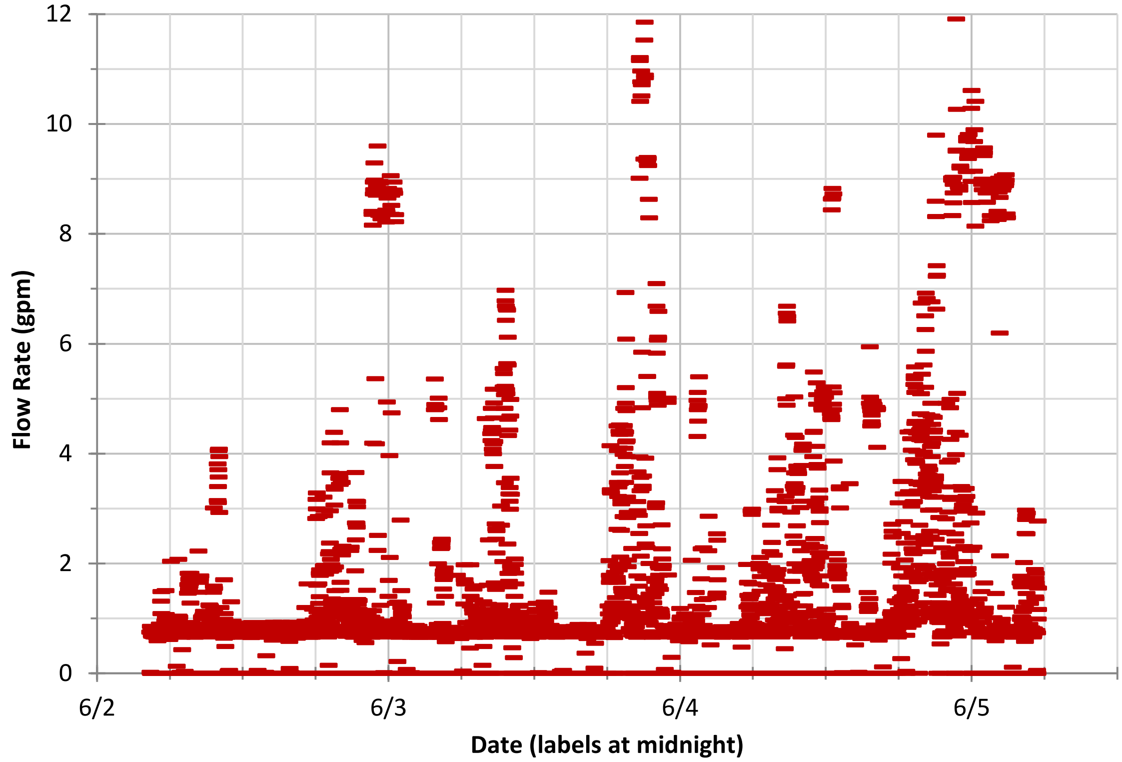

*Figure 22***.** Water heater inlet flow rate at Hotel #1 during the first 73 hours.

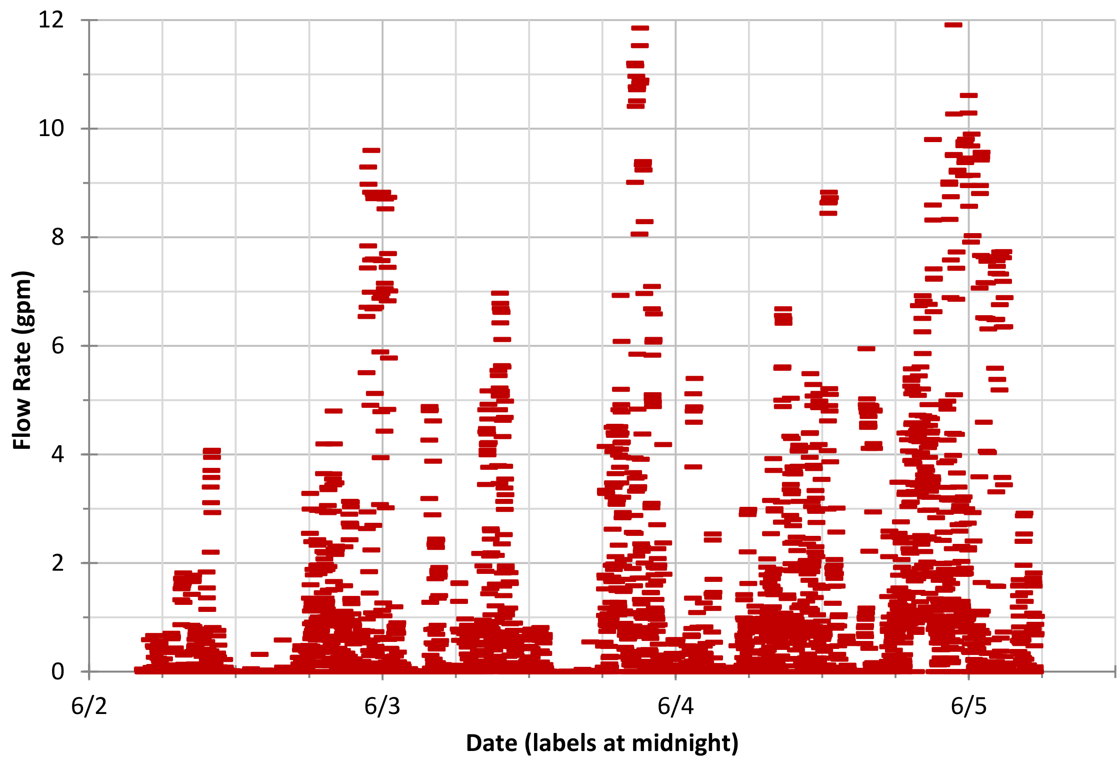

*Figure 23***.** Calculated cold water flow rate at Hotel #1 during the first 73 hours.

Hot water draw profiles for Hotel #1 were created using this calculated cold water flow rate. Despite covering a time period of roughly three days, as opposed to 15 days, the profiles that exclude recirculation flow are assumed to be more accurate because the recirculation flow accounts for more than one third of the total tank inlet flow. Figure 24 shows the hot water draw profile for Hotel #1 that is a composite of the calculated cold water flow rate over the first 73 hours of data collection.

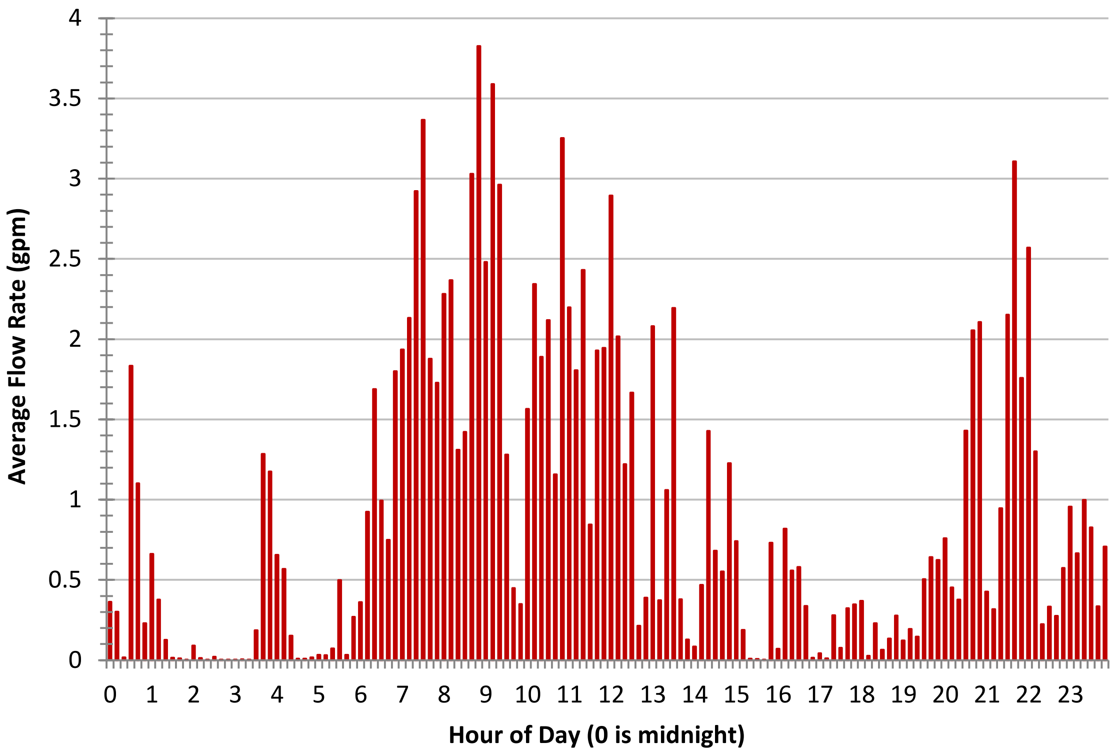

*Figure 24***.** Calculated cold water flow rate at Hotel #1 during the first 73 hours.

This profile is somewhat similar to the one for Hotel #2. Some notable differences are the small peak at 4:00 am, the taller morning and evening peaks, the lower flow during the afternoon, the small peak at 1:00 am, and the large peak's clear division at 10:00 am. The total hot water consumption for the first 73 hours of data collection averaged 1327 gallons per day.

Hotel #2

The flow meter at Hotel #2 measured the flow rate of cold water going to the water heaters. It does not include the flow of the recirculation loop. The profiles for Hotel #2 are presented with the same scale as the Hotel #1 profiles to allow for easy comparison. Figure 25 shows the general hot water draw profile for Hotel #2. Note the lack of flow during early-morning hours. The total hot water consumption for the test period averaged 1299 gallons per day.

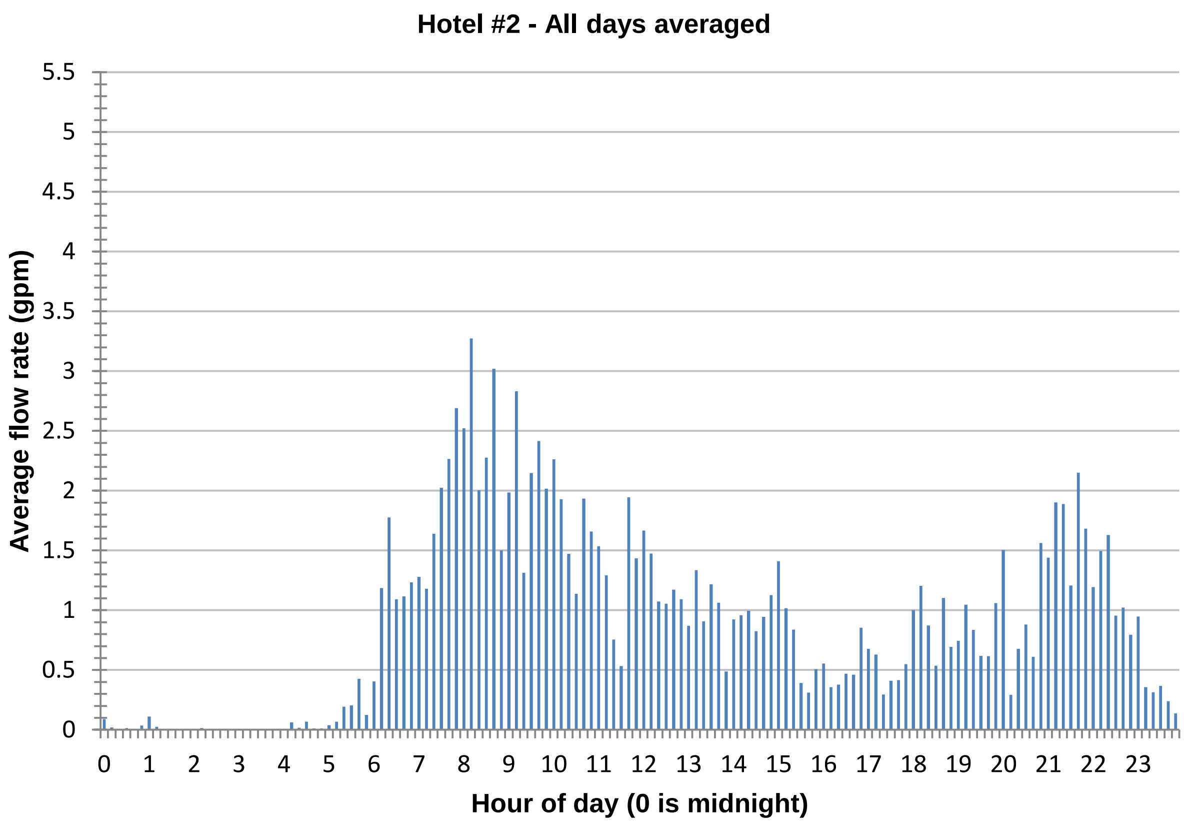

*Figure 25***.** Hot water draw profile for Hotel #2: average for all days.

The morning shower peak for Hotel #2 is shorter and wider than Hotel#1's morning peak, though both peaks are centered at 8:00 am. The ratio of laundry peak size to shower peak size is larger for the Hotel #2 profile.

Figures 26 and 27 show the profile for the average weekday and average weekend day, respectively, at Hotel #2. Weekdays averaged 1303 gallons per day of hot water use, and weekend days averaged 1290 gallons.

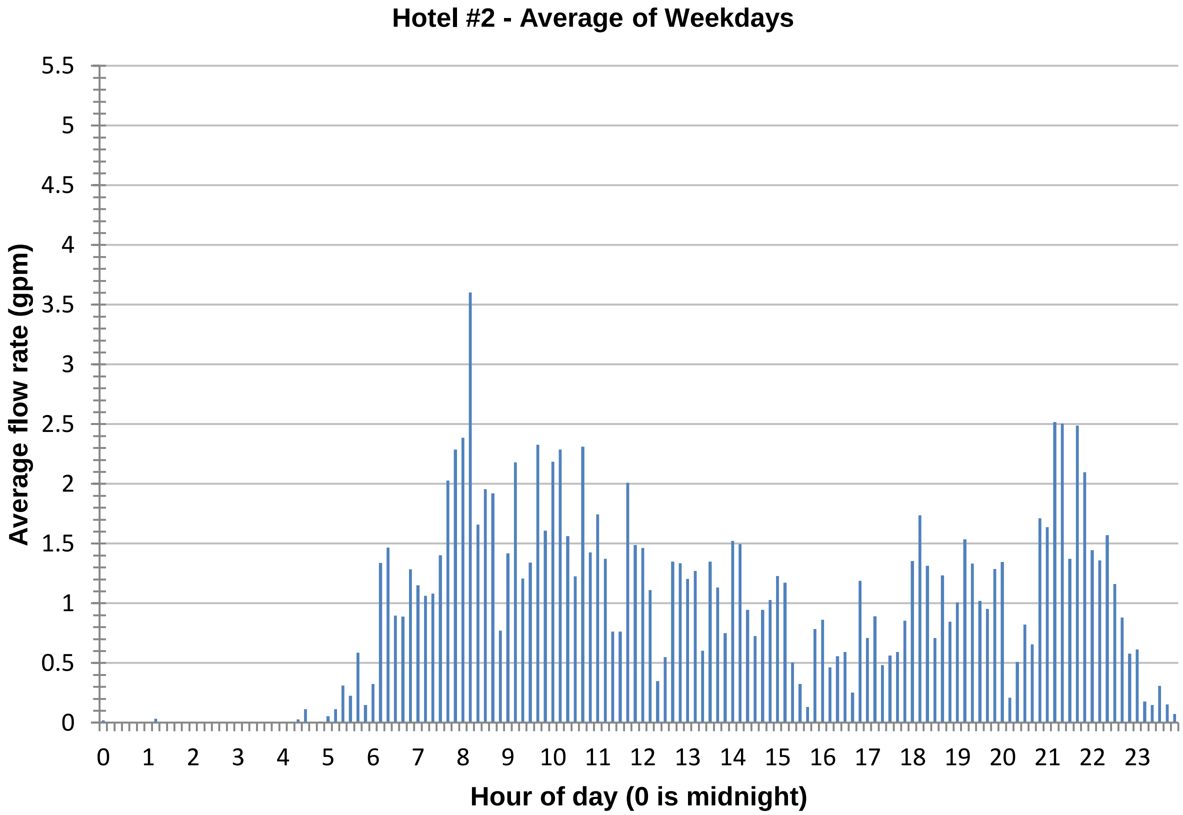

*Figure 26***.** Hot water draw profile for Hotel #2: average for weekdays.

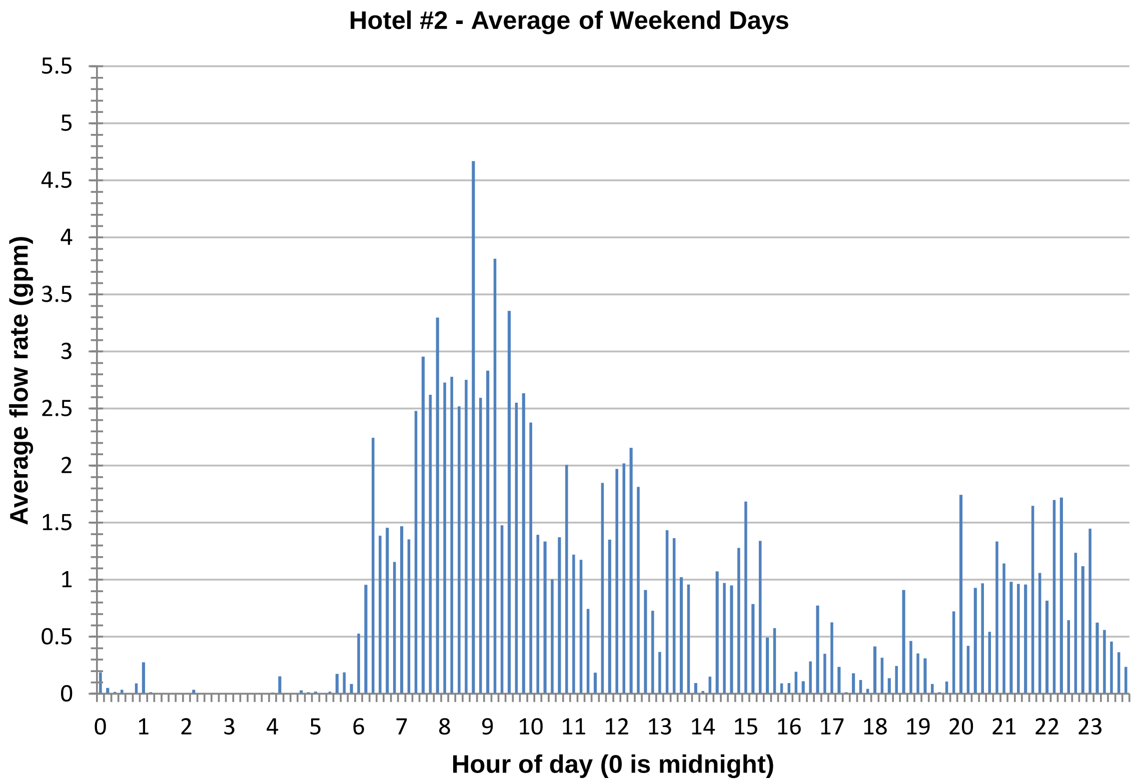

*Figure 27***.** Hot water draw profile for Hotel #2: average for weekend days.

The weekday profile contains few distinct peaks. Even the morning shower peak is difficult to distinguish from the various laundry peaks. Also notable is that the morning and nighttime peaks are approximately the same height. The weekend profile, with its taller morning peak and secondary nighttime peak, exhibits a pattern similar to that in the Hotel #1 profile.

Hot Water Usage and Occupancy

The daily percentage of rooms occupied (occupancy rate) for each testing period was obtained from the hotel owners via the questionnaire described in Chapter 3 of this paper. Check-in time for each hotel was 3:00 pm, so a "day," as defined in this section, is the period of time between 3:00 pm and 2:59 pm the next day. The correlation of hot water consumption and occupancy rate was investigated.

Hotel #1

Figure 28 shows the occupancy rate at Hotel #1 for each test day. Figure 29 shows the total hot water consumption at Hotel #1 for the same days.

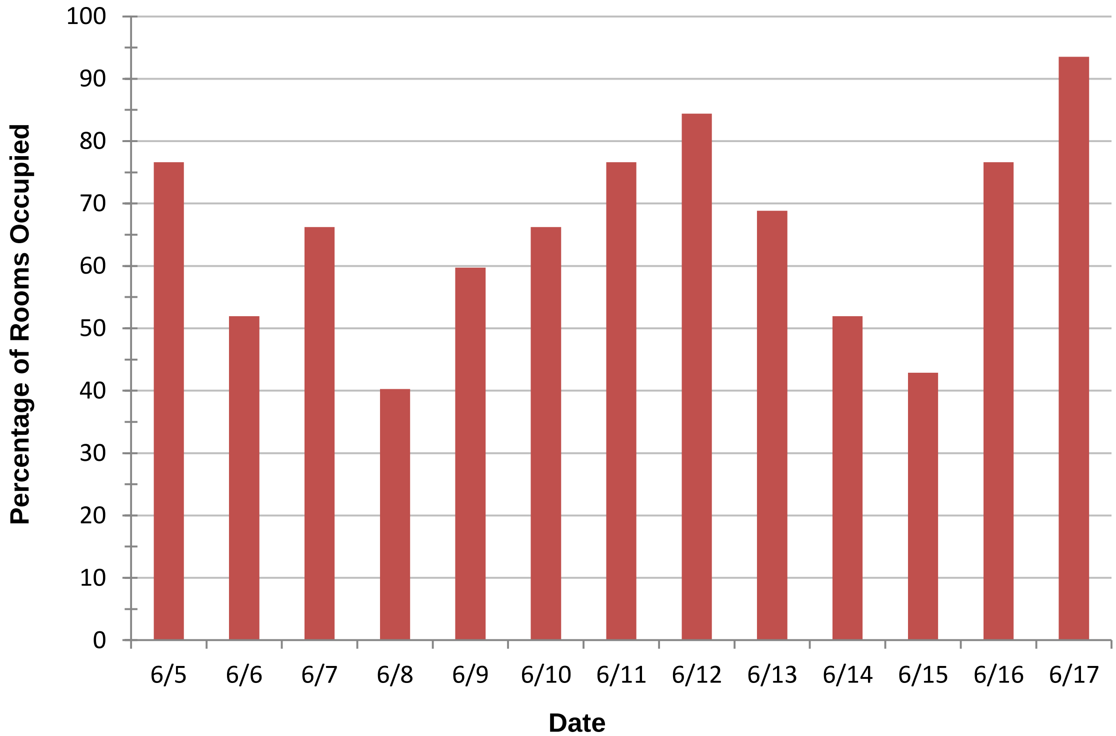

*Figure 28***.** Percentage of rooms occupied at Hotel #1 by date.

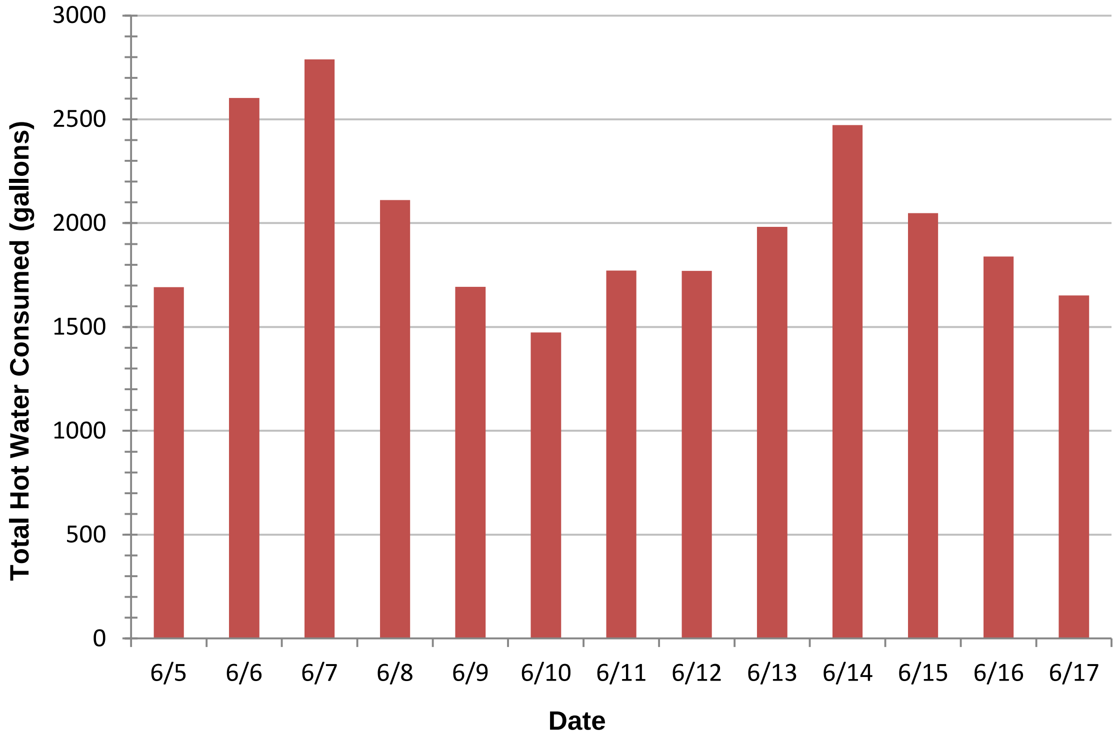

*Figure 29***.** Total hot water consumed at Hotel #1 by date.

One might expect that more hot water would be consumed at the hotel when more rooms are occupied, but this does not appear to be the case. The scatterplot in Figure 30 makes this clearer. If anything, more hot water seems to be consumed when *fewer* rooms are occupied, although the small sample size precludes any definitive statement about this.

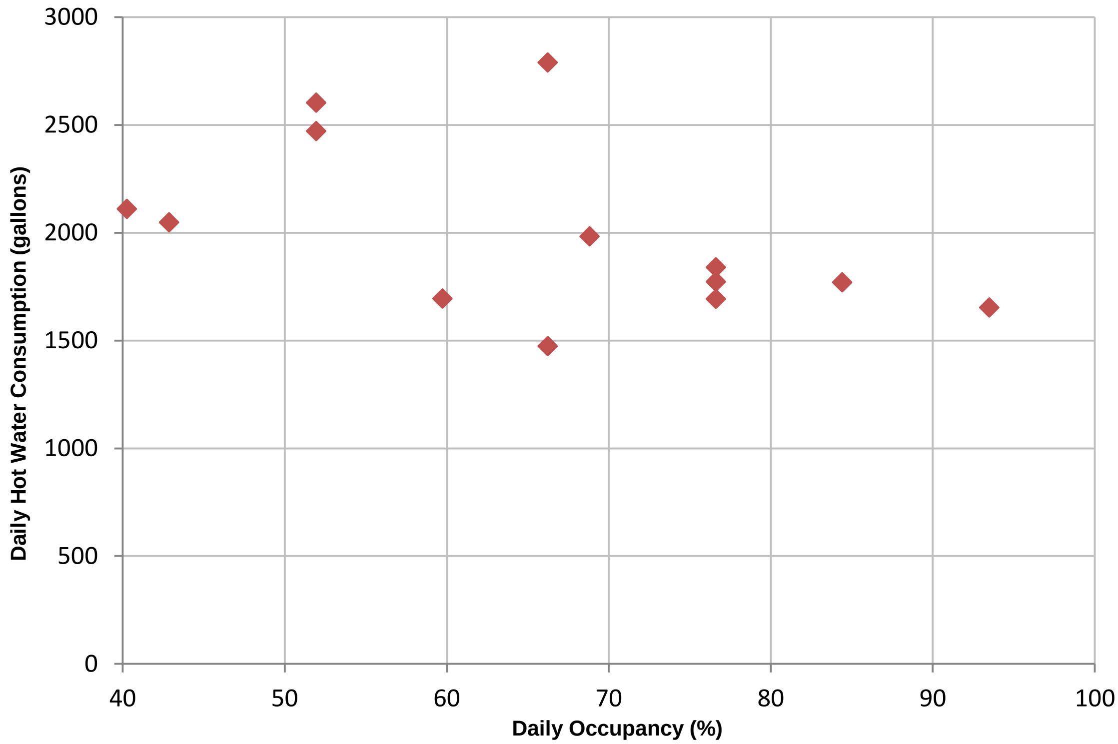

*Figure 30***.** Daily hot water consumption in gallons as a function of occupancy rate at Hotel #1.

Most authors of previous studies reported hot water consumption in units of gallons/day/room, rather than in gallons/day/occupied-room. This is most likely because occupancy data was unavailable to them. The hot water consumption as a function of occupancy rate at Hotel #1 is shown in Figures 31 and 32, with units of gallons/day/room and gallons/day/occupied-room, respectively. This pair of graphs highlights the importance of reporting hot water consumption data in units of gallons/day/occupied-room. At Hotel #1, the number of occupied rooms affects the hot water consumption per occupied room. This can be at least partially attributed to the inclusion of recirculation flow in the flow measurement at this hotel. The daily recirculation flow remains nearly constant, so when fewer rooms are occupied, the recirculation flow makes up a larger percentage of the total daily hot water flow.

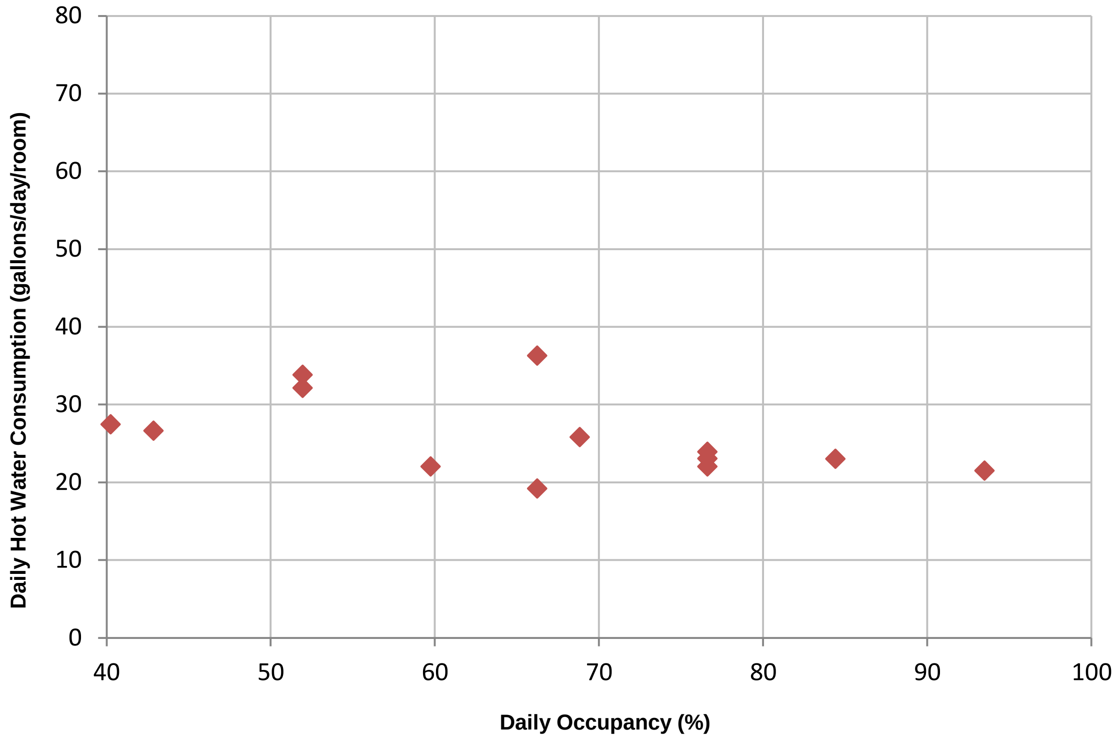

*Figure 31***.** Daily hot water consumption in gallons/day/room as a function of occupancy rate at Hotel #1.

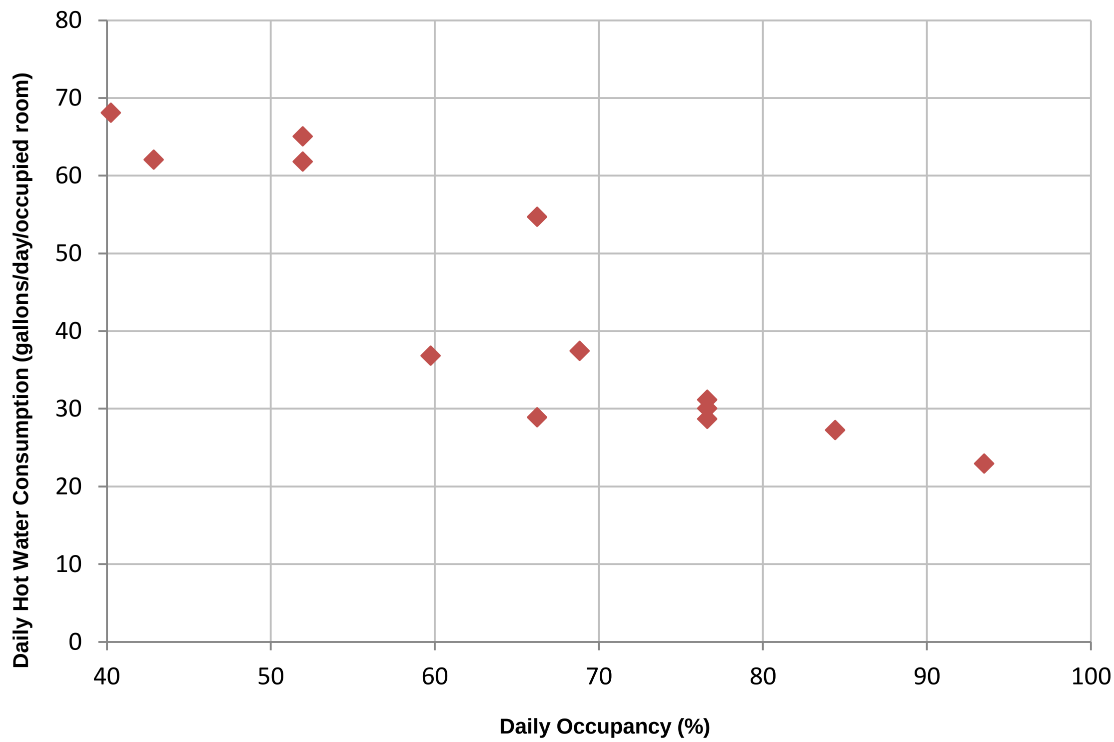

*Figure 32***.** Daily hot water consumption in gallons/day/occupied-room as a function of occupancy rate at Hotel #1.

The correlation was not analyzed for the Hotel #1 data with the recirculation flow excluded because there are only data for three days.

Hotel #2

Figure 33, below, shows the occupancy rate at Hotel #2 for each test day. Figure 34 shows the total hot water consumption at Hotel #2 for the same days.

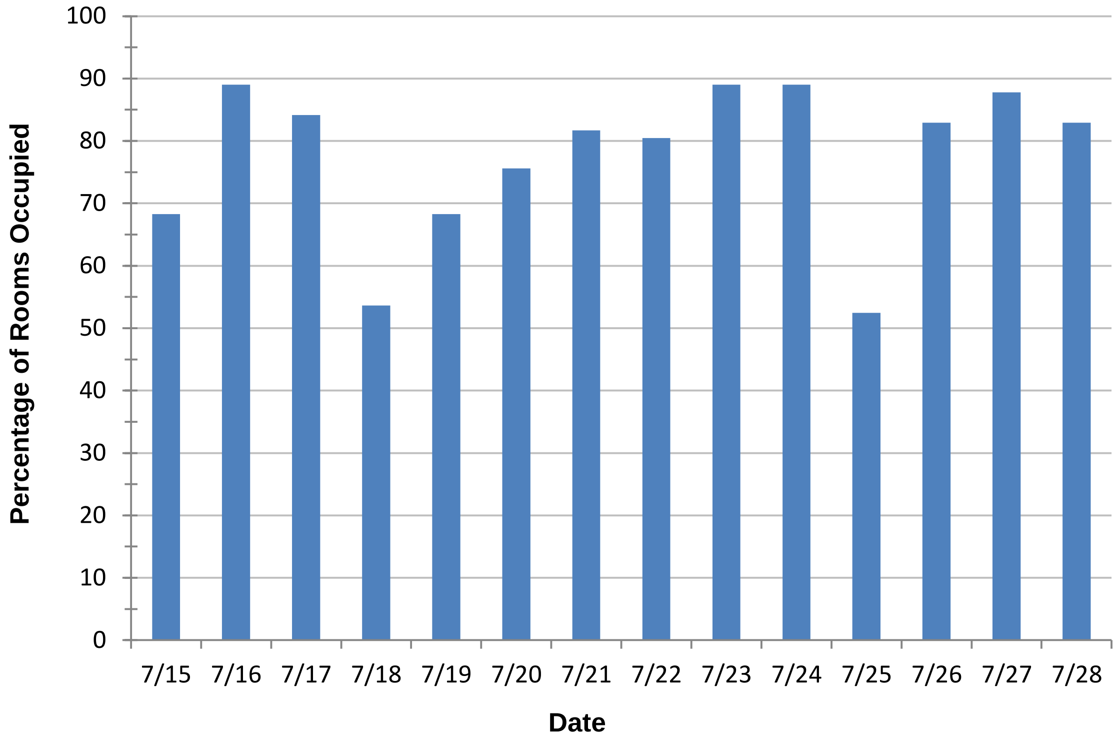

*Figure 33***.** Percentage of rooms occupied at Hotel #2 by date.

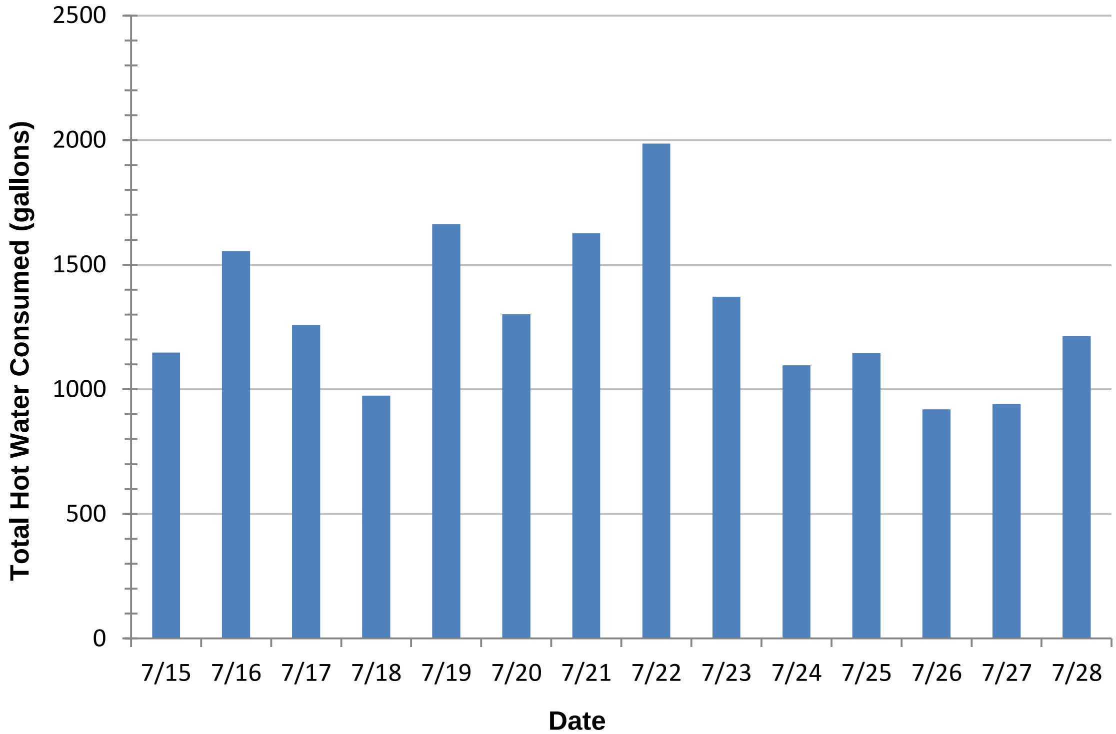

*Figure 34***.** Total hot water consumed at Hotel #2 by date.

The occupancy rate and daily hot water consumption, as is the case with Hotel #1, do not appear to be correlated. Figure 35 shows the absence of even a small correlation.

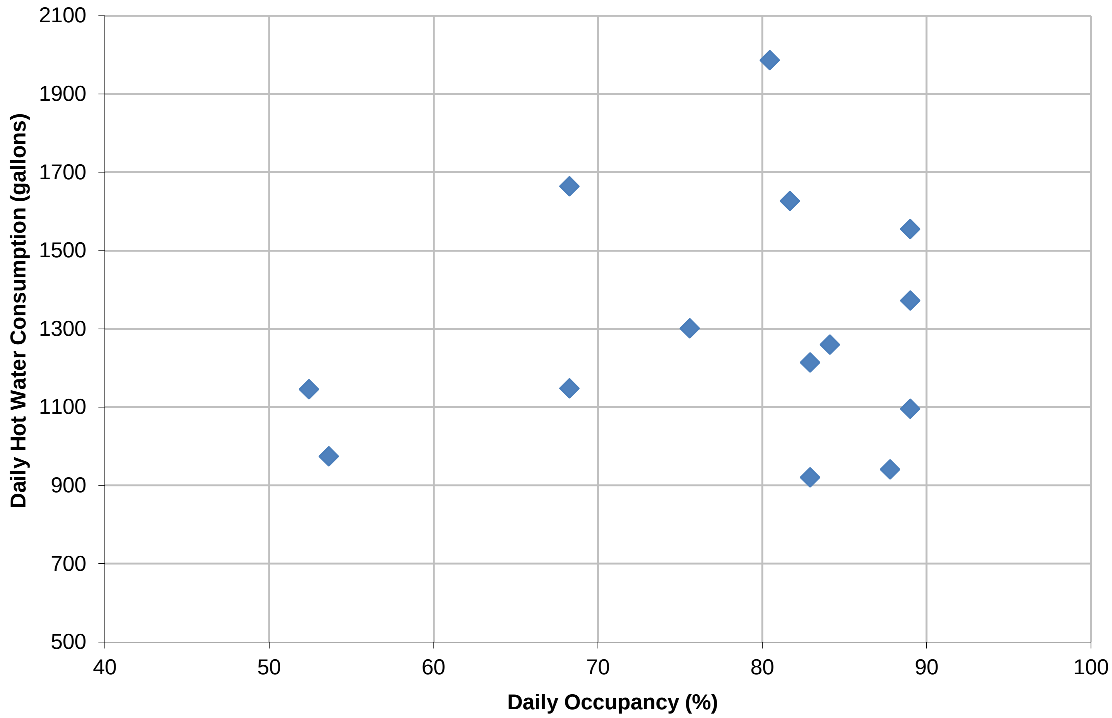

Figure 35. Daily hot water consumption in gallons as a function of occupancy rate at Hotel #2.

As is the case with the Hotel #1 data, reporting the hot water consumption in units of gallons/day/room and of gallons/day/occupied-room produces different results. But in the case of Hotel #2, the difference cannot be attributed to recirculation flow because recirculation flow was not included in the hot water flow measurement. The hot water consumption as a function of occupancy rate at Hotel #2 is shown in Figures 36 and 37, with units of gallons/day/room and gallons/day/occupied-room, respectively.

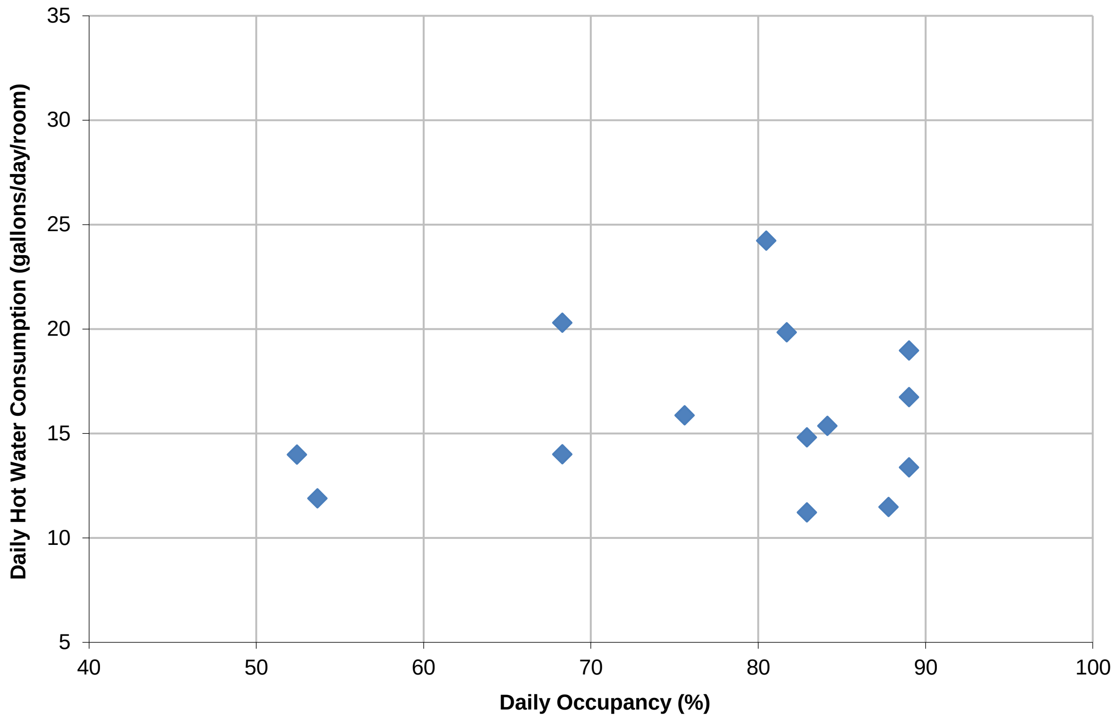

*Figure 36***.** Daily hot water consumption in gallons/day/room as a function of occupancy rate at Hotel #2.

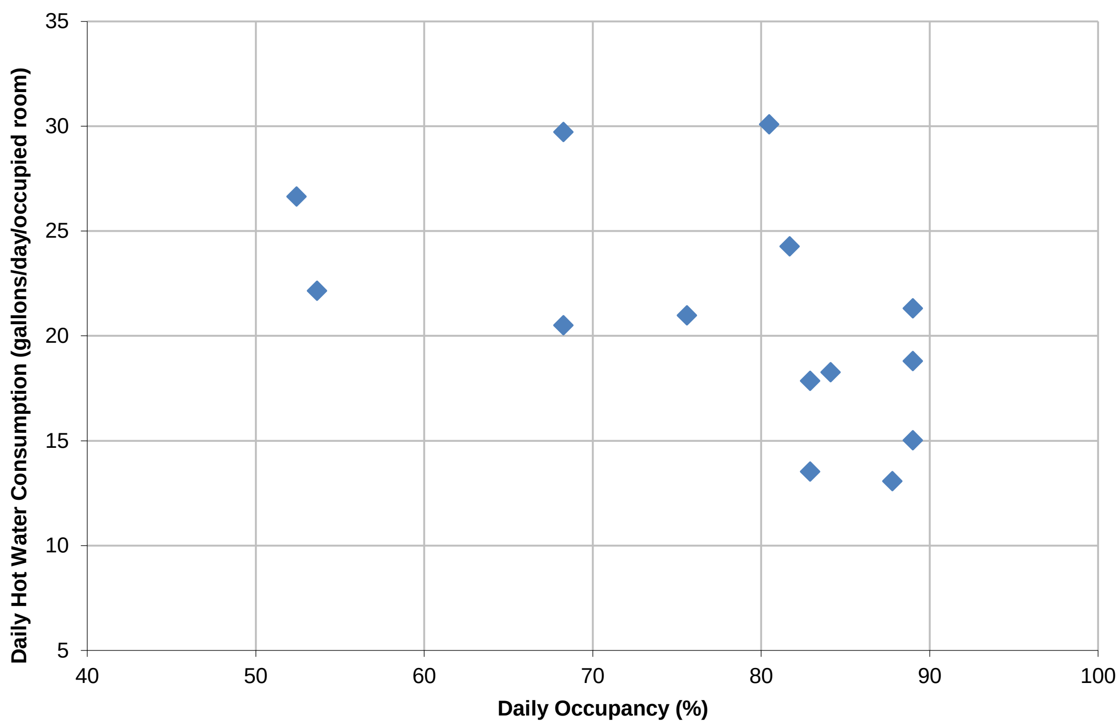

Figure 37. Daily hot water consumption in gallons/day/occupied-room as a function of occupancy rate at Hotel #1.

Although the R-squared value for the data in Figure 34 is small, the difference in results from the two ways of reporting hot water consumption per room is not negligible. Dividing the total consumption by the number of occupied rooms rather than by the number of total rooms has a greater effect on low-occupancy days than on high-occupancy days. The difference is possibly an indication that the number of laundry machine cycles using hot water at this particular hotel is mostly independent of the percentage of rooms occupied.

The ASHRAE standard, as previously mentioned in the review of related literature, would indicate that Hotel #2 would consume between 10 and 14 gallons/day/room (close to 12 gallons/day/room by interpolation). This estimate would not be valid if the Hotel #2 data sample presented here were representative of the actual annual consumption. Further data collection is recommended.

CHAPTER 5

MODELING

TRNSYS Model Description

TRNSYS is an energy system simulation application. It has been available commercially since 1975 (Thermal Energy System Specialists, 2009) and is well-established in both academia and industry. The user constructs a virtual system from a library of components, which includes solar thermal collectors, thermal storage tanks, pumps, boilers, etc. The user then connects the components with “wires” that indicate which variable values to pass from one component to another, and in which direction to pass them. For example, a pump can be connected to a water storage tank such that the pump will pass to the tank information about the fluid’s temperature and flow rate at each time step during the simulation time period. Any variable can be printed to a file and/or plotted directly to a TRNSYS graph.

In this study, the main components are a water storage tank with a submersed heat exchanger, a water boiler unit, an array of solar thermal collectors, a water circulation pump, a differential controller to govern the pump, an hourly weather input file, and a component to read an external spreadsheet containing a water draw profile. A one-hour time step is used, meaning TRNSYS calculates the value of all variables in the system every hour of the simulation time period.

Domestic Hot Water Model and Model Validation

The solar thermal side of the system was turned off, leaving the boiler as the sole heat source. For Hotel #1, the composite water draw profile determined for Hotel #1 provided the flow rate information to the boiler at all time steps during the simulation runs. The simulation time period was set to June 3 through June 16, a period of 13 days. The TRNSYS boiler component was set to a volume equal to the sum of all three real water heaters (119 gallons each), and the heating capacity was set to the sum of all three real heaters' capacities (199,000 BTU/hr each). The actual heat provided by the three water heaters at Hotel #1 during that time period was 1,745,500 BTU. The TRNSYS boiler values for tank insulation and temperature set point were adjusted until the simulated heat production closely approximated the actual heat production for that time period. The simulation came to within 2% of the actual value.

For Hotel #2, the composite water draw profile determined for Hotel #2 provided the flow rate information to the boiler at all time steps during the simulation runs. The simulation time period was set to July 14 through July 29, a period of 15 days. The TRNSYS boiler component was again set to a volume equal to the sum of all three real water heaters, and the heating capacity was set to the sum of all three real heaters' capacities (199,000 BTU/hr each). The actual heat provided by the three water heaters at Hotel #2 during that time period was 8,879,900 BTU. The TRNSYS boiler values for tank insulation and temperature set point were adjusted until the simulated heat production closely approximated the actual heat production for that time period. The simulation came to within 2.4% of the actual value.

Solar Thermal System Design

The Annual Solar Fraction is an often-reported measure of a solar water heating system's performance, but it does not tell the whole story. A performance metric that is more useful for business owners is the life-cycle savings, which means the total savings provided by the system over its useful lifespan. In this study, the annualized life-cycle savings (ALCS) is reported. It indicates the average annual savings provided by the system, after accounting for expenses associated with it (parts, installation, and operation and maintenance).

Hotel #1

The composite water draw profile excluding recirculation flow for Hotel #1 was used as the water draw input for the simulations in the following solar thermal system design optimization sections.

Optimization of Collector Tilt Angle. The FR:CA ratio was set to 0.0467 gpm/ft^2, and the SV-CA ratio was set at 2.5 gallons/ft^2. The collector tilt angle was varied from 15 to 50 degrees from horizontal. This process was repeated for collector areas of 599.5 ft^2 and 899.3 ft^2. The results are shown in Figure 38. The optimized tilt angle for both collector areas is 33 degrees from horizontal.

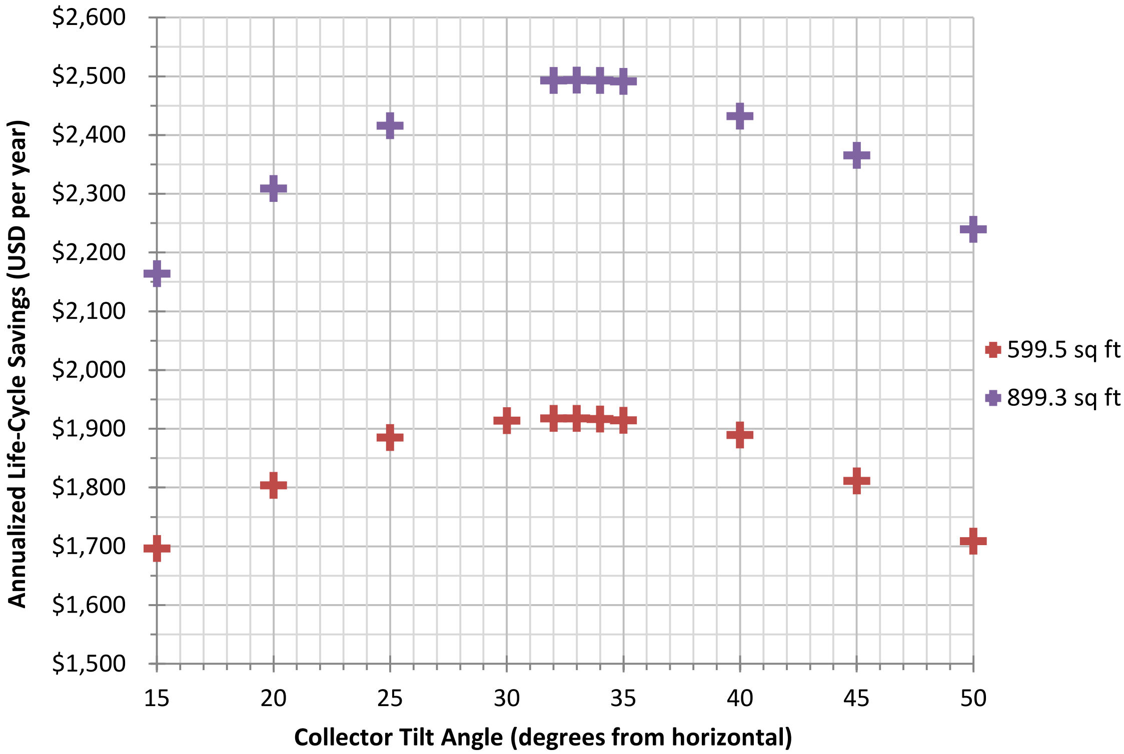

*Figure 38***.** Annualized life-cycle savings as a function of collector tilt angle for two different collector areas.

Optimization of Collector Flow Rate

The solar storage tank volume was set to 2000 gallons. The collector flow rate (i.e., the rate of flow of the heat transfer fluid through the collectors) was varied from 0.007 to 0.24 gallons per minute per square foot of collector area. This process was repeated for collector areas of 224.8 ft^2, 337.2 ft^2, 449.6 ft^2, 599.5 ft^2, 749.4 ft^2, 899.3 ft^2, 1049.2 ft^2, 1348.9 ft^2, and 1648.7 ft^2. Figure 39 shows the effect of the flow-rate-to-collector-area (FR:CA) ratio on the ALCS of the solar thermal system.

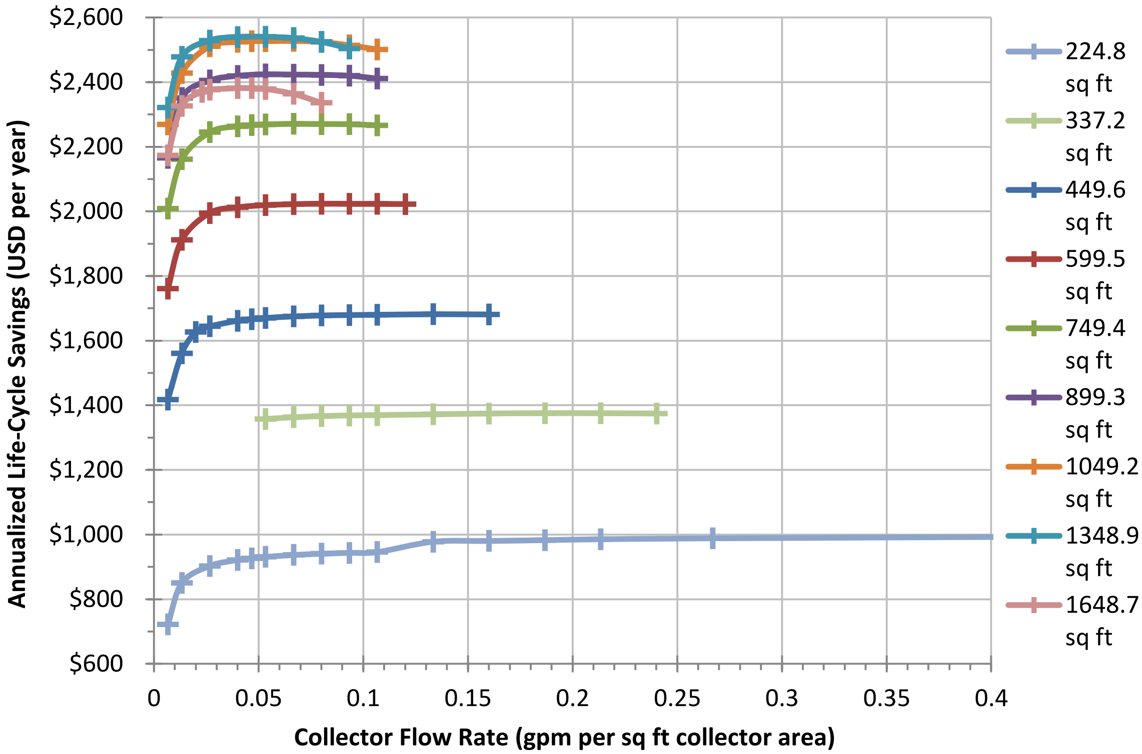

*Figure 39***.** Annualized life-cycle savings as a function of collector flow rate for a system with a 2000-gallon storage tank.

Evident in Figure 39 is that the optimized FR:CA ratio decreases as the collector area increases. A power curve was fit to the optimized FR:CA points (Figure 40). The equation for determining the optimized FR:CA is: flow rate (gpm/ft^2) = 34.351 * collector area (ft^2) ^ -0.9606.

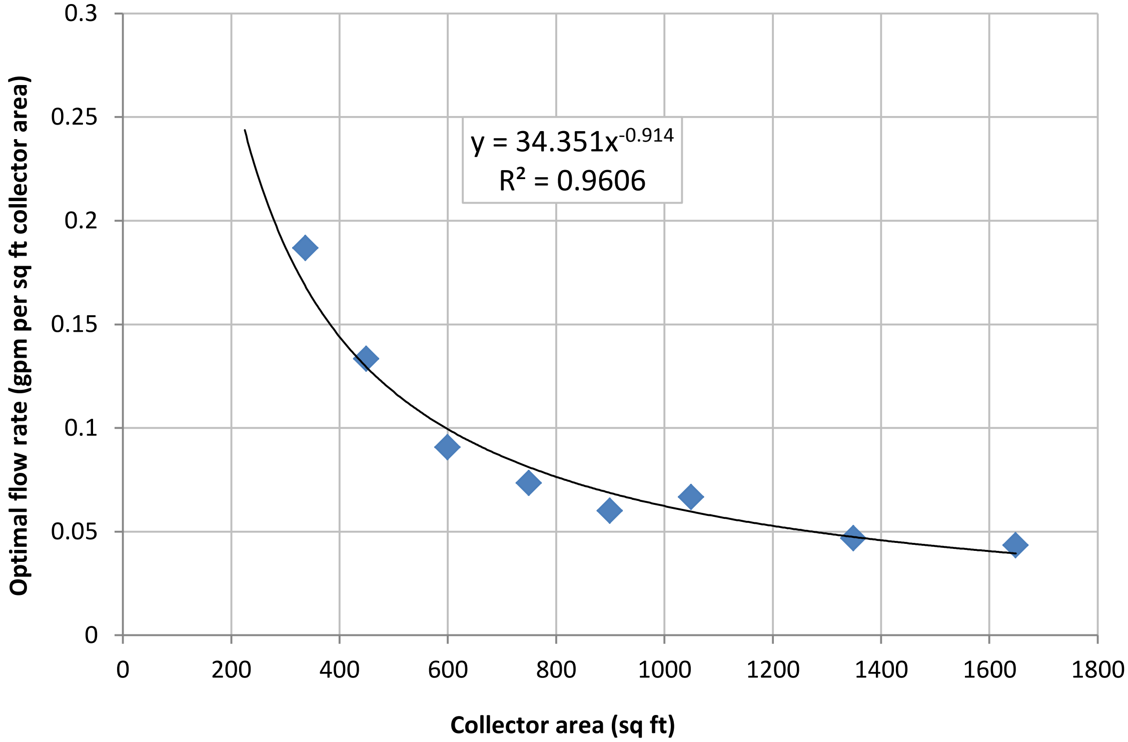

*Figure 40***.** Optimized FA:CA ratio for Hotel #2.

In order to determine whether the optimum FR:CA ratio depends on storage tank volume, the process was repeated for a solar storage tank volume of 4000 gallons. These results are shown in Figure 41. The optimum FR:CA ratio is approximately the same for both storage tank volumes.

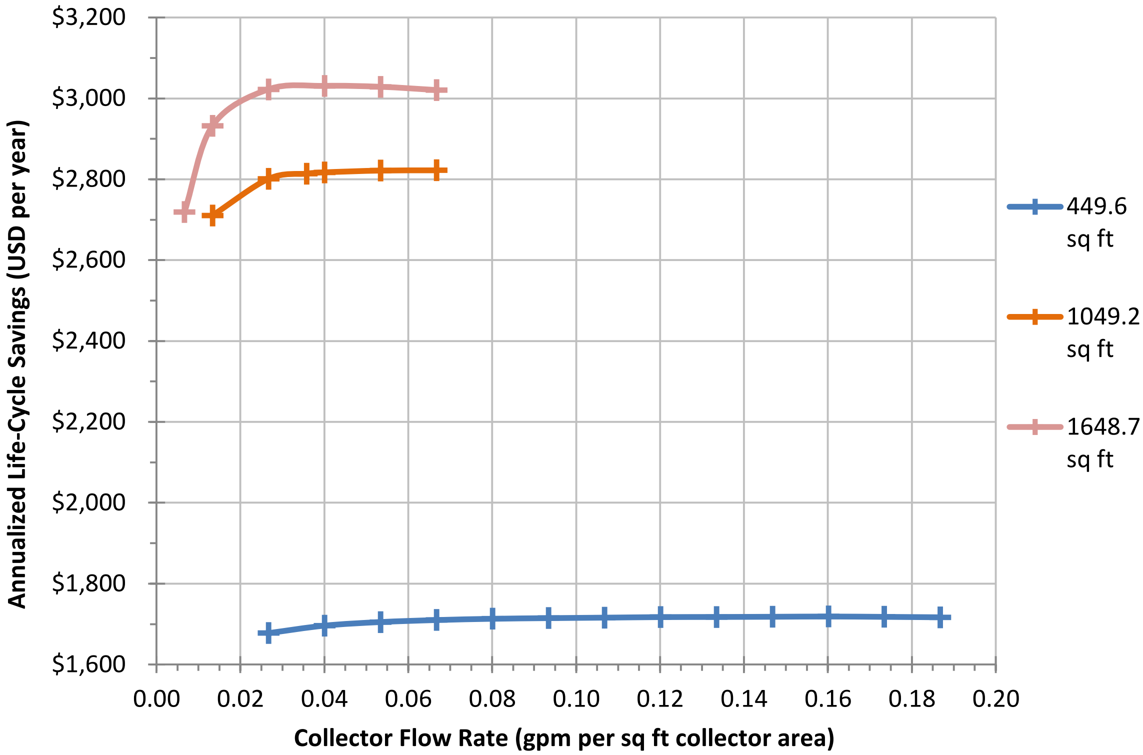

*Figure 41***.** Annualized life-cycle savings as a function of collector flow rate for a system with a 4000-gallon storage tank.

Optimization of Solar Storage Tank Volume

The FR:CA ratio was input according to the aforementioned equation. The solar storage tank volume was varied from 0.5 to 8 gallons per square foot of collector area. This process was repeated for collector areas of 299.8 ft^2, 559.5 ft^2, 1124.1 ft^2, and 1648.7 ft^2. Figure 42 shows the effect of the storage-volume-to-collector-area (SV:CA) ratio on the ALCS of the solar thermal system. Each curve represents one of the four collector areas.

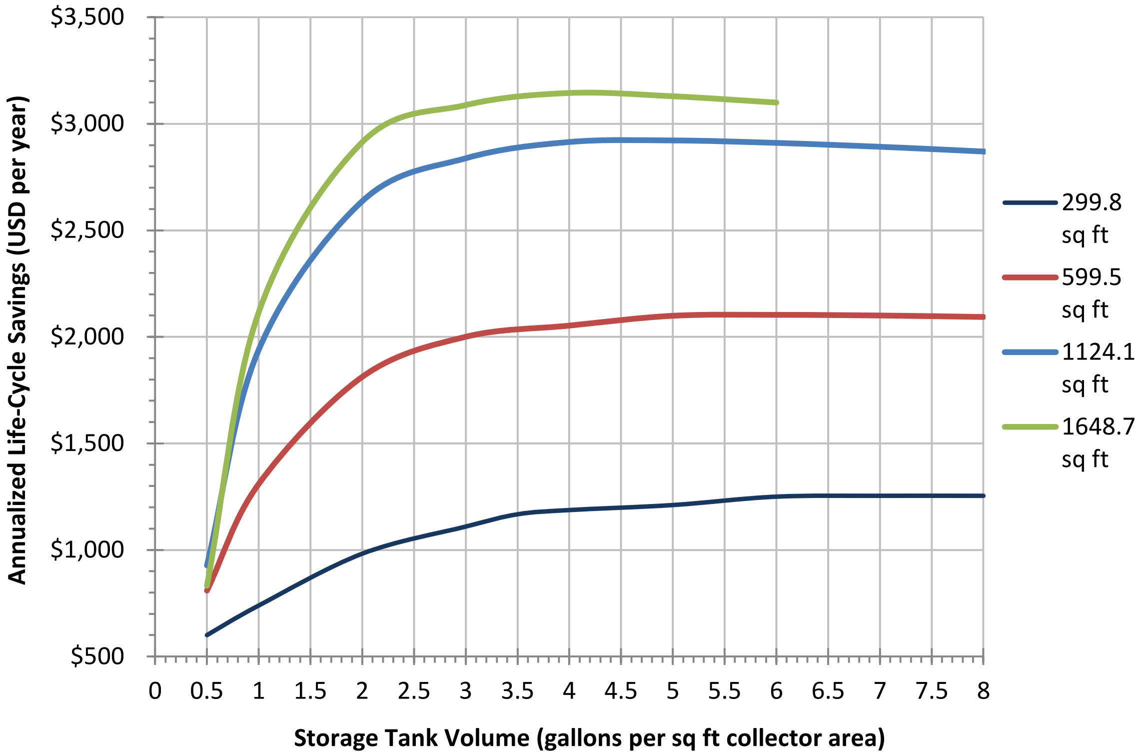

*Figure 42***.** Annualized life-cycle savings as a function of solar storage tank volume.

A SV:CA ratio of four gallons/ft^2 comes close to maximizing the ALCS for all collector areas. If space is a concern, the ratio can, in most cases, be reduced to three with little penalty to the ALCS.

Hotel #2

The composite water draw profile for Hotel #2 was used as the water draw input for the simulations in the following solar thermal system design optimization sections.

Optimization of Collector Tilt Angle. The FR:CA ratio was set to 0.0467 gpm/ft^2, and the SV-CA ratio was set at 2.5 gallons/ft^2. The collector tilt angle was varied from 15 to 50 degrees from horizontal. This process was repeated for collector areas of 599.5 ft^2 and

899.3 ft^2. The results are shown in Figure 43. The optimized tilt angle for both collector areas is 34 degrees from horizontal.

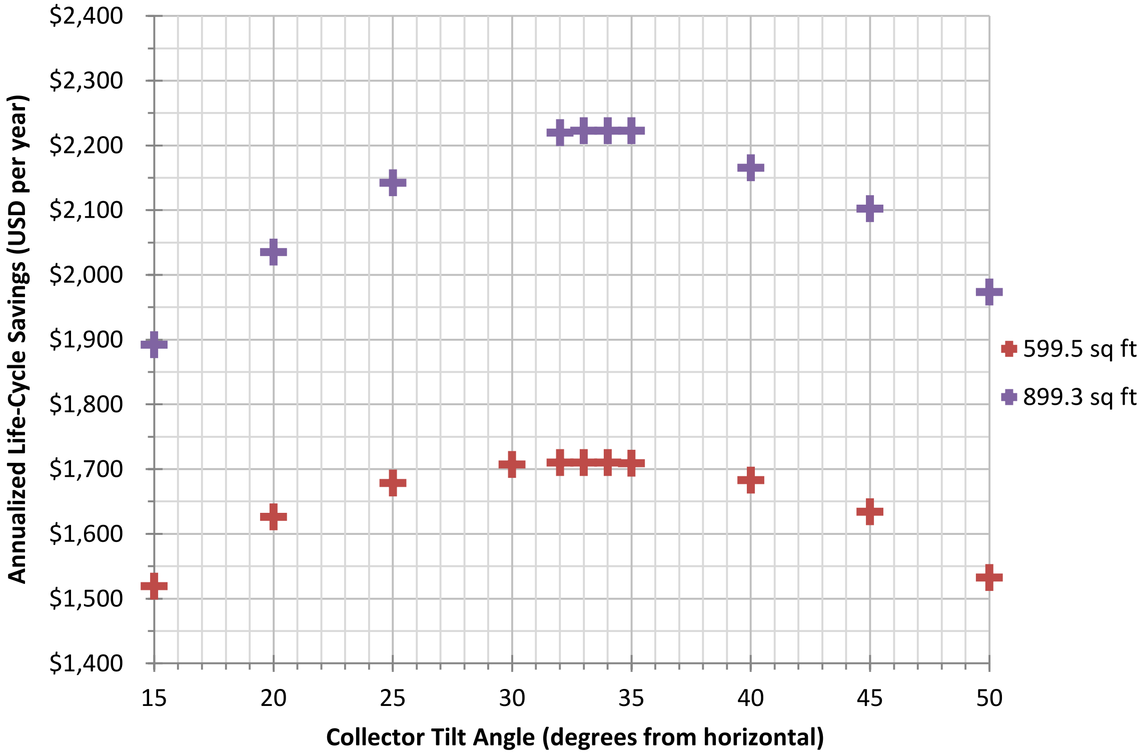

*Figure 43***.** Annualized life-cycle savings as a function of collector tilt angle for two different collector areas.

Optimization of Collector Flow Rate

The solar storage tank volume was set to 2000 gallons. The collector flow rate (i.e., the rate of flow of the heat transfer fluid through the collectors) was varied from 0.007 to 0.13 gallons per minute per square foot of collector area. This process was repeated for collector areas of 224.8 ft^2, 449.6 ft^2, 749.4 ft^2, 1049.2 ft^2, and 1648.7 ft^2. Figure 44 shows the effect of the flow-rate-to-collector-area (FR:CA) ratio on the ALCS of the solar thermal system.

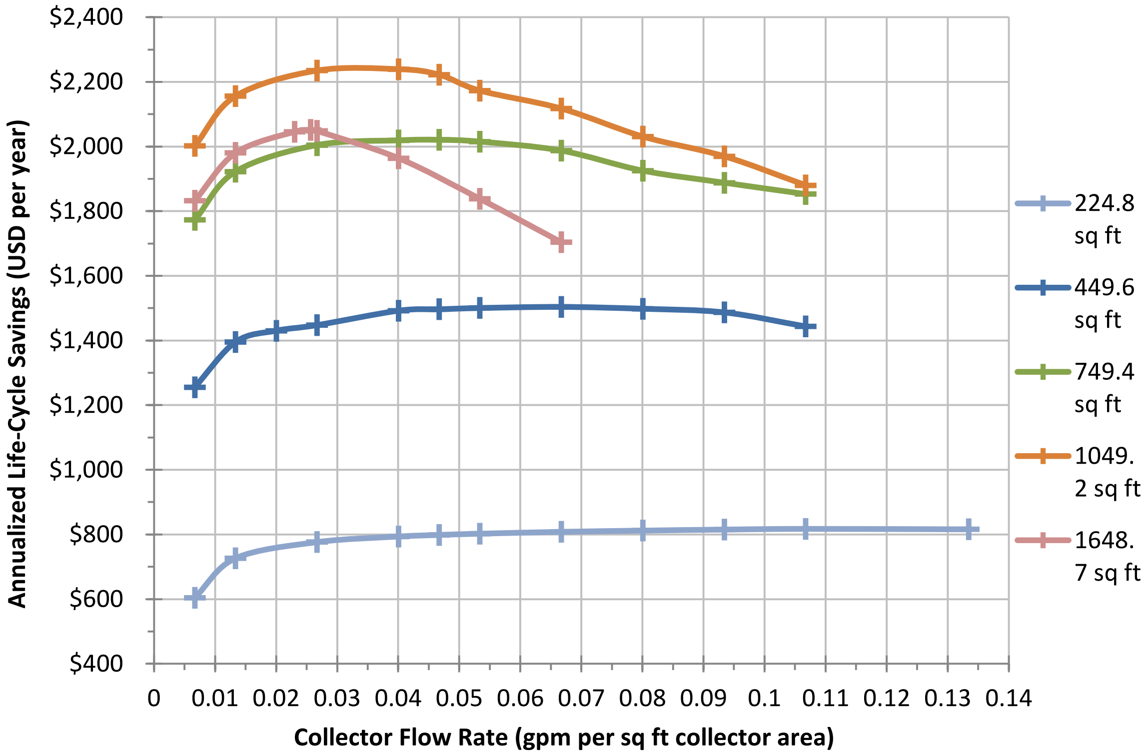

*Figure 44***.** Annualized life-cycle savings as a function of collector flow rate for a system with a 2000-gallon storage tank.

Evident in Figure 39 is that the optimized FR:CA ratio decreases as the collector area increases. A power curve was fit to the optimized FR:CA points (Figure 45). The equation for determining the optimized FR:CA is: flow rate (gpm/ft^2) = 5.8983 * collector area (ft^2) ^ -0.734.

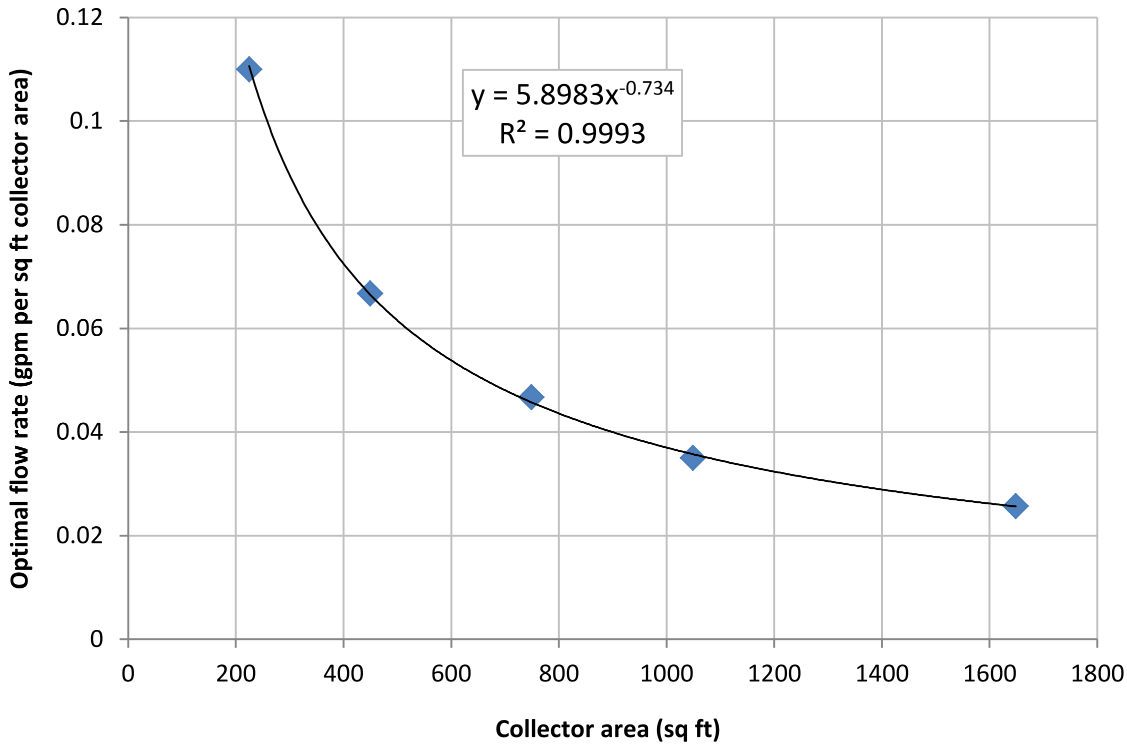

*Figure 45***.** Optimized FA:CA ratio for Hotel #2.

In order to determine whether the optimum FR:CA ratio depends on storage tank volume, the process was repeated for a solar storage tank volume of 4000 gallons. These results are shown in Figure 46. The optimum FR:CA ratio is approximately the same for both storage tank volumes.

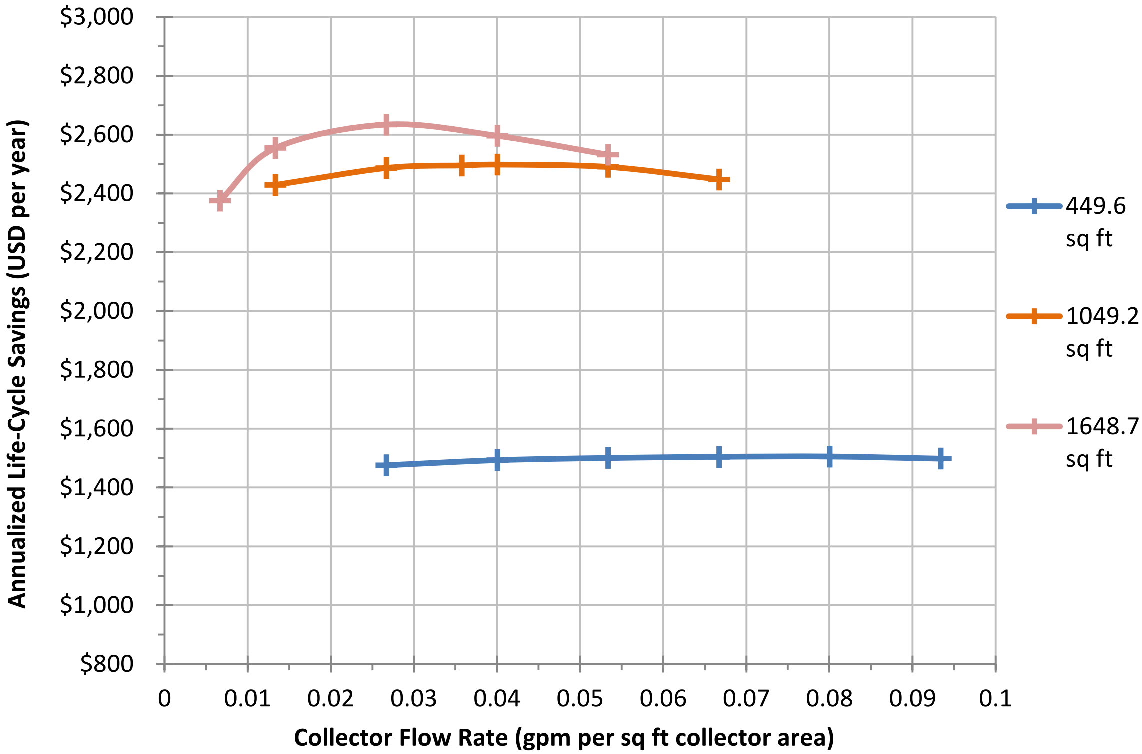

*Figure 46***.** Annualized life-cycle savings as a function of collector flow rate for a system with a 4000-gallon storage tank.

Optimization of Solar Storage Tank Volume

The FR:CA ratio was input according to the aforementioned equation. The solar storage tank volume was varied from 0.5 to 8 gallons per square foot of collector area. This process was repeated for collector areas of 299.8 ft^2, 559.5 ft^2, 1124.1 ft^2, and 1648.7 ft^2. Figure 47 shows the effect of the storage-volume-to-collector-area (SV:CA) ratio on the ALCS of the solar thermal system. Each curve represents one of the four collector areas.

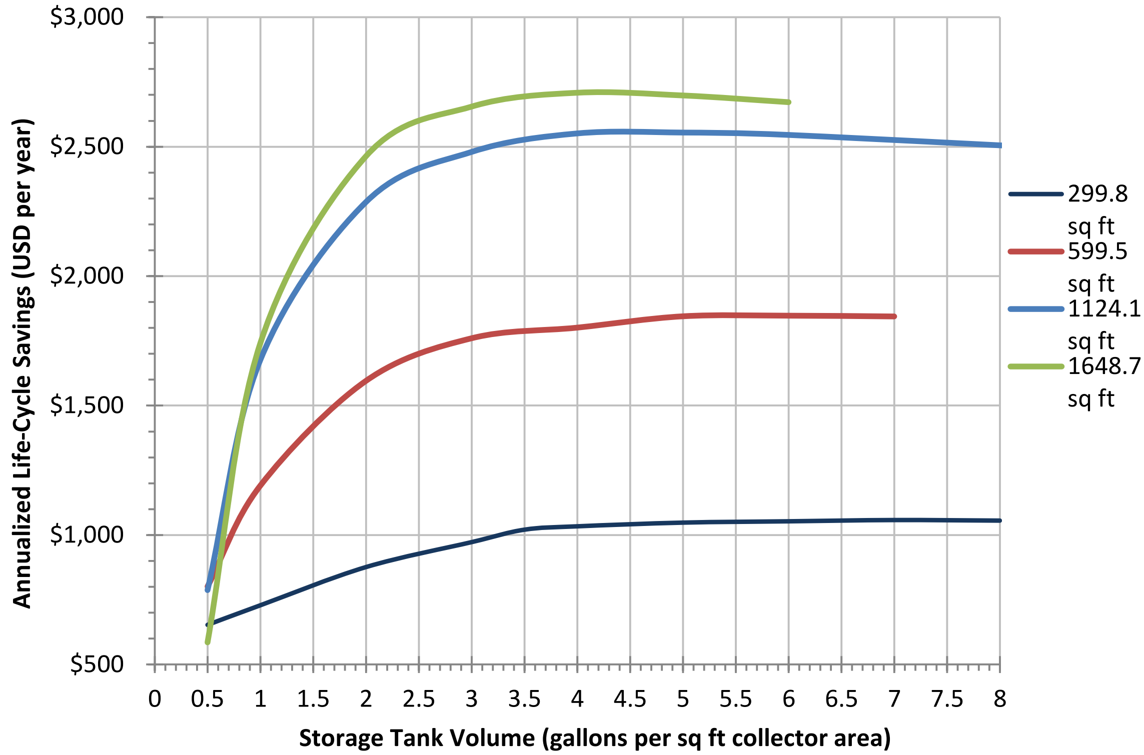

*Figure 47***.** Annualized life-cycle savings as a function of solar storage tank volume.

A SV:CA ratio of four gallons/ft^2 comes close to maximizing the ALCS for all collector sizes. If space is a concern, the ratio can be reduced to three with little penalty to the ALCS.

Optimization of Discretionary Hot Water Draw Profile

The "discretionary water draw profile" is the part of the hotel's hot water draw profile that can be transposed or reassigned to different times of day. This part of the profile is most likely composed of hot water used for laundry services. Non-discretionary hot water use is composed of the bigger usage peaks caused by guest showers in the mornings and evenings.

The discretionary profile was rearranged to produce hot water use scenarios that are different from the actual current situation at the hotels. In other words, the hot water used by laundry machines and for cleaning was reassigned to different times of day. The measured profile and each of the modified profiles were used as inputs into the TRNSYS model. The optimum values for the collector tilt angle, the FR:CA ratio, and the SV:CA ratio were also used as inputs. Then, for each profile, the ALCS was determined for a range of collector areas.

Hotel #1

For Hotel #1, all of the hot water usage between 12:00 pm and 8:00 pm was considered discretionary. Discretionary draw accounts for approximately 23% of the total daily flow. Figures 48-52 show the profiles analyzed for Hotel #1. Table 3 is a summary of all the Hotel #1 profiles, with a brief description of each one.

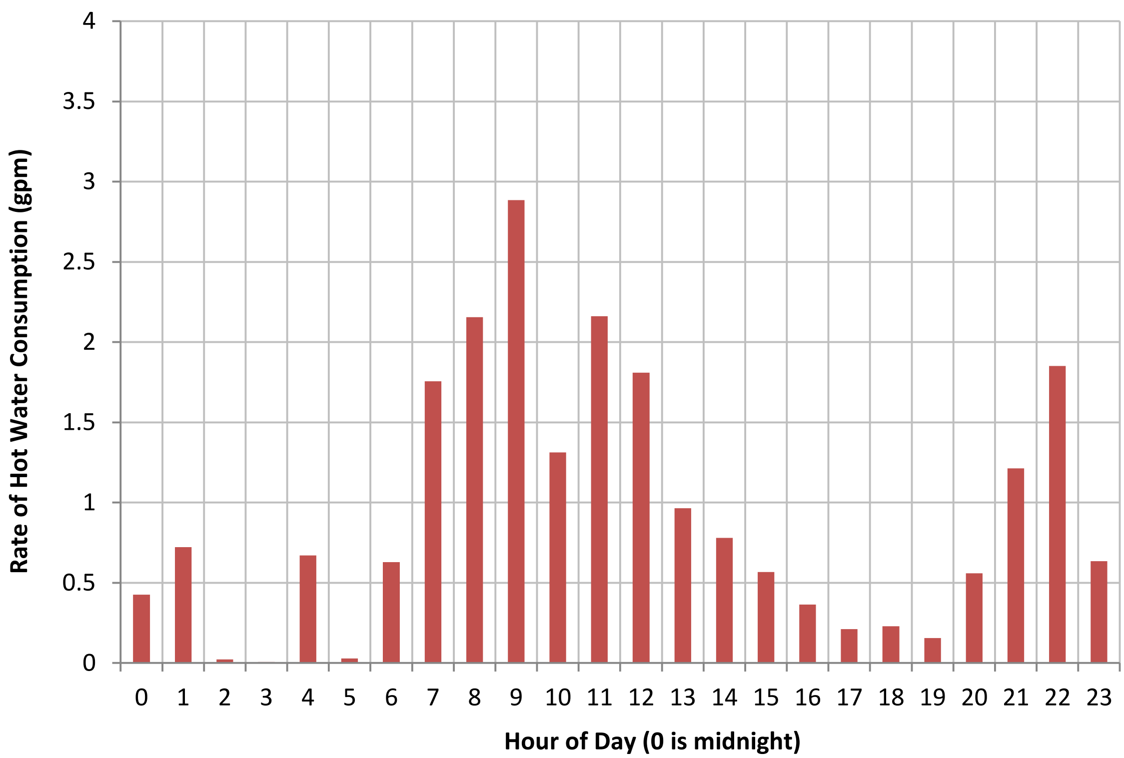

*Figure 48***.** Profile 1A—the composite profile created from measured data.

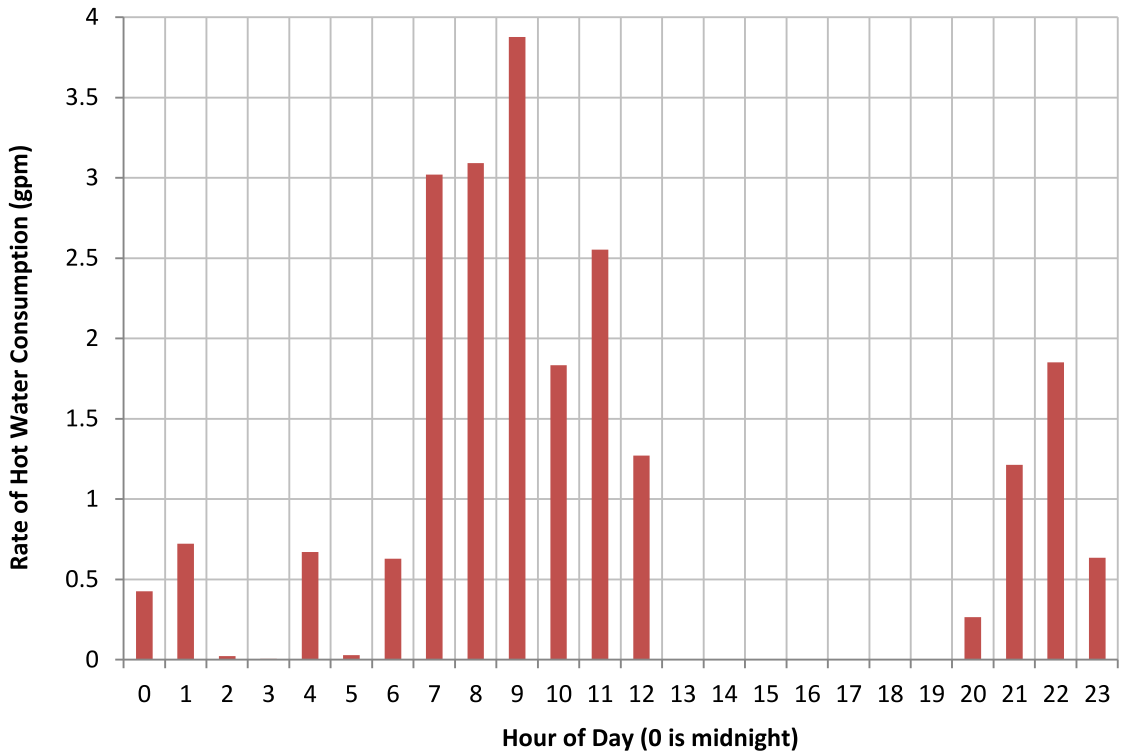

*Figure 49***.** Profile 1B—the discretionary draw moved to morning hours.

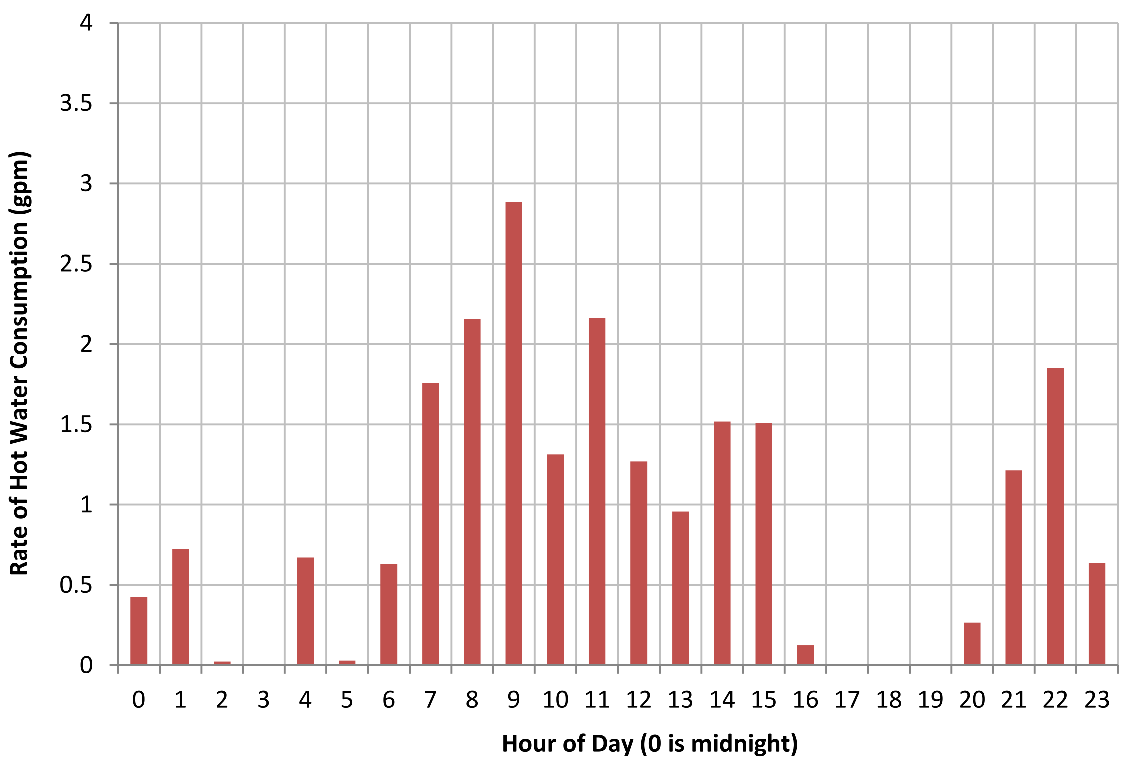

*Figure 50***.** Profile 1C—the discretionary draw consolidated and centered around 2:00 pm.

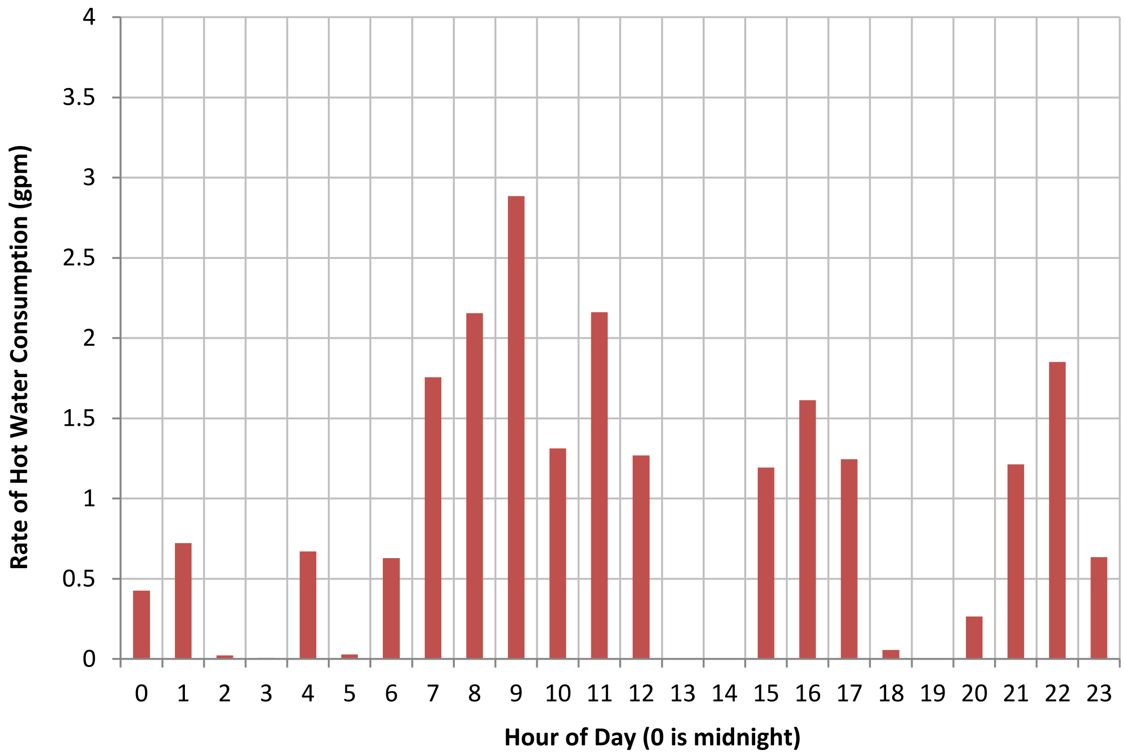

*Figure 51***.** Profile 1D—the discretionary draw consolidated and centered around 4:00 pm.

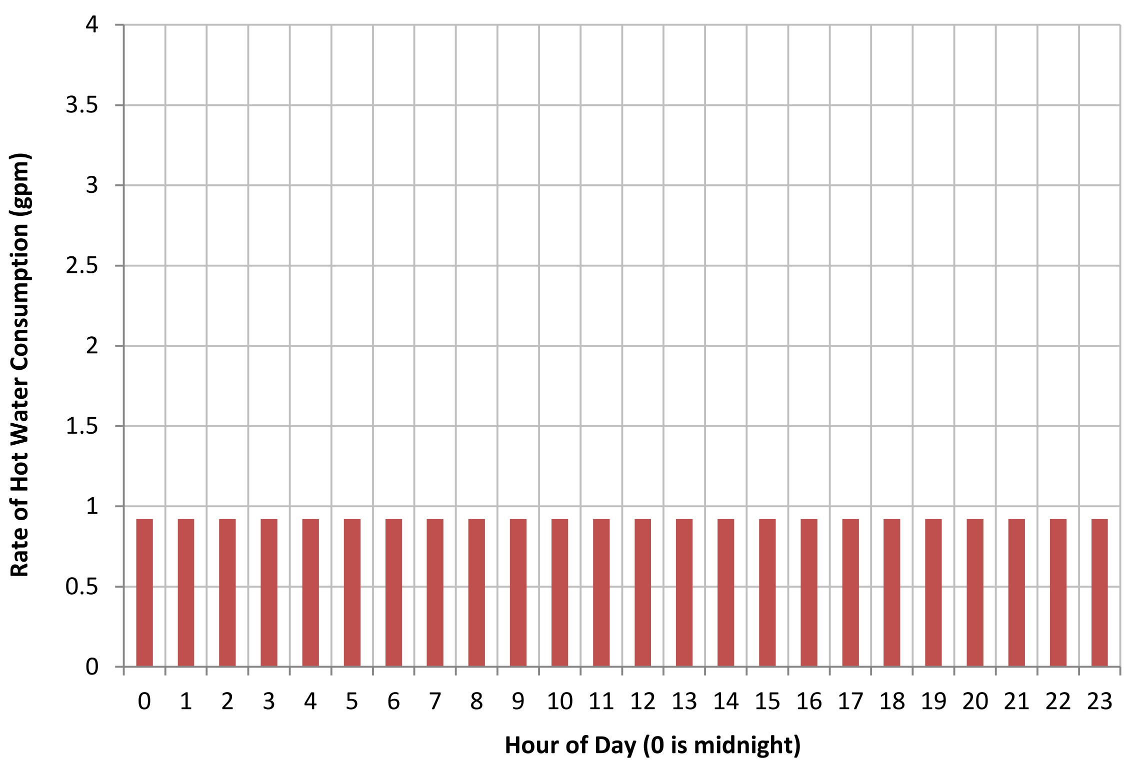

*Figure 52***.** Profile 1E—constant draw.

Table 3.
Summary of Hot Water Draw Profiles for Hotel #1

Profile	Description
1A	measured from data
1B	discretionary draw moved to morning
1C	discretionary draw centered at 2:00 pm
1D	discretionary draw centered at 4:00 pm
1E	constant draw

Figure 53 shows the ALCS for each profile over a range of collector areas at Hotel #1.

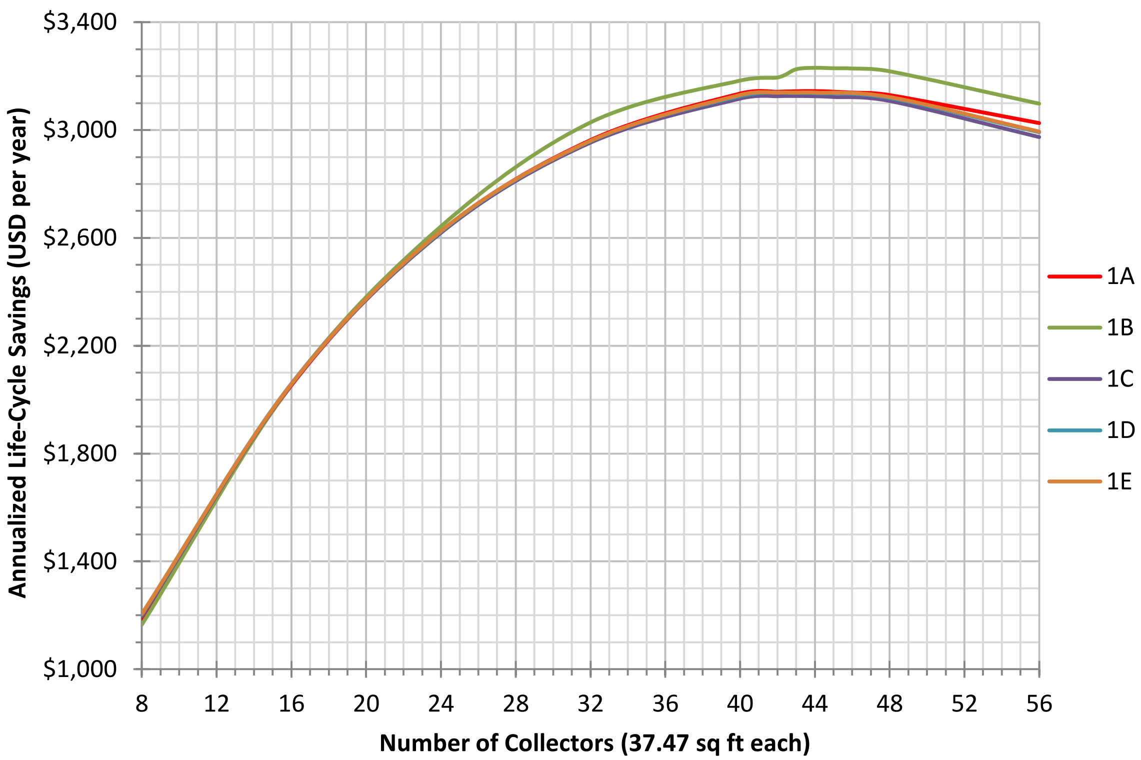

*Figure 53***.** ALCS for each Hotel #1 draw profile as a function of collector area.

The profile with the discretionary draw moved to the morning time (Profile 2B) yields an ALCS 2.7% higher than that for the measured draw profile (Profile 2A). The optimal number of 4-by-10 foot collectors is 44 (1648.7 ft^2). The corresponding optimal collector flow rate is 65 gpm (1.48 gpm/ft^2 collector area), and the optimal storage volume is 6500 gal. The system will save $64,600 over 20 years and will pay for itself in 4.58 years.

Even a drastic, unrealistic shift in the hot water draw profile (Profile 1E) has very little effect on the SDHW system performance. It may be that the large storage volume compensates for the less-than-ideal draw profiles.

Hotel #2

For Hotel #2, all of the hot water usage between 11:00 am and 8:00 pm was considered discretionary. Discretionary draw accounts for approximately 55% of the total daily flow. Figures 54-58 show the profiles analyzed for Hotel #2. Table 4 is a summary of all the Hotel #2 profiles, with a brief description of each one. Figure 59 shows the ALCS for each profile over a range of collector areas at Hotel #2.

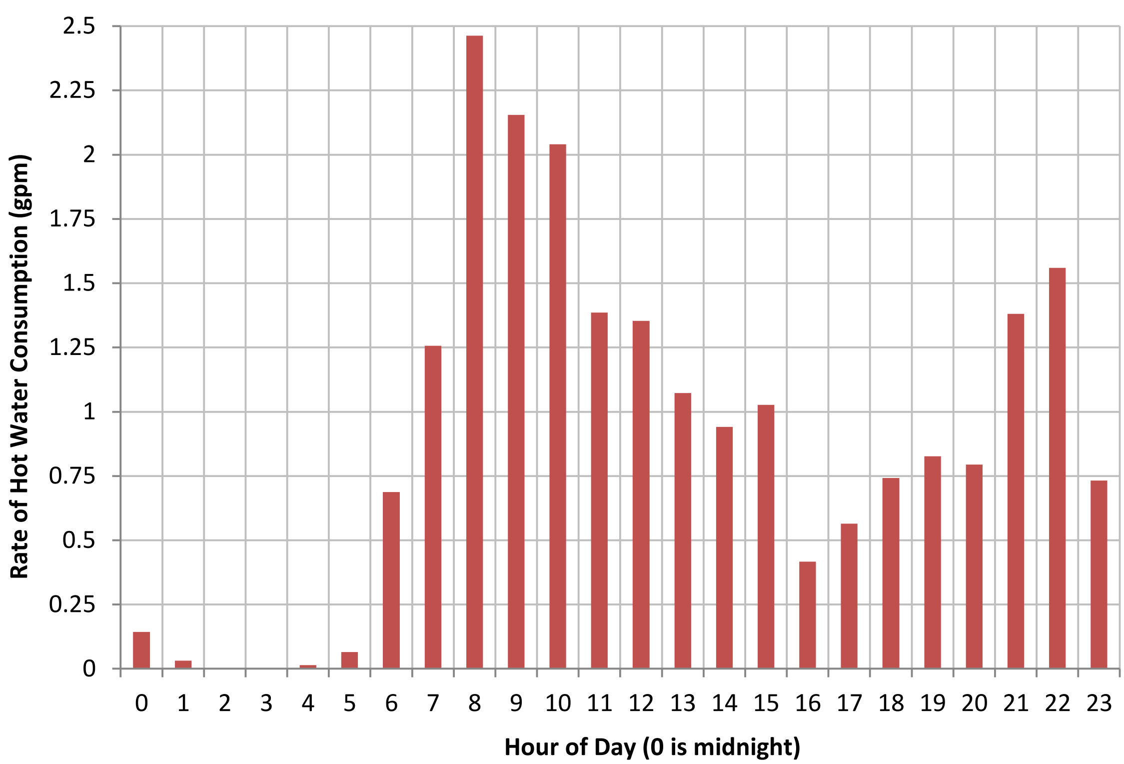

*Figure 54***.** Profile 2A—the composite profile created from measured data.

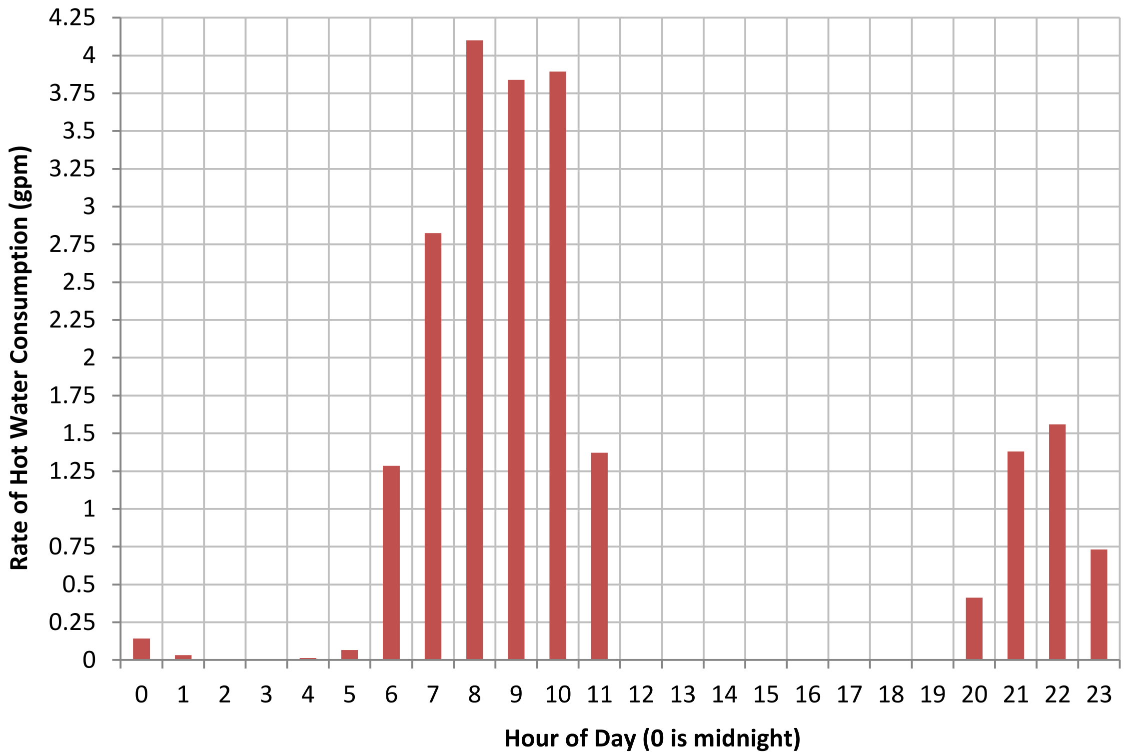

*Figure 55***.** Profile 2B—the discretionary draw moved to morning hours.

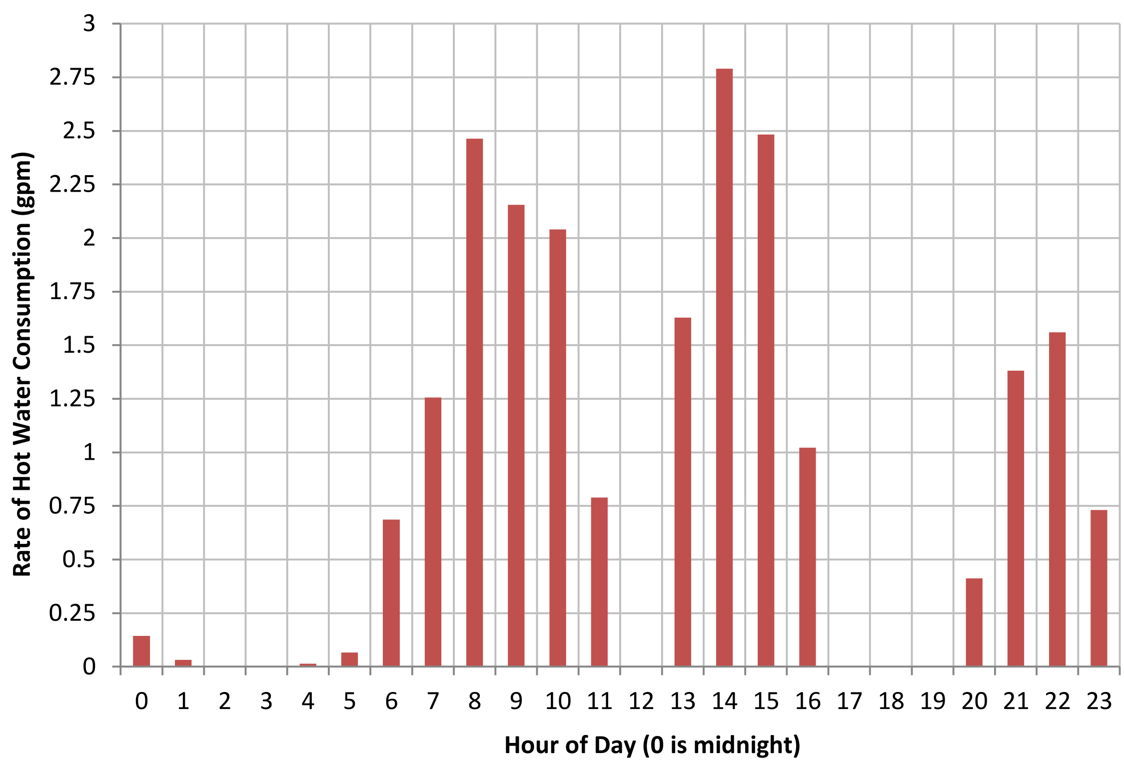

*Figure 56***.** Profile 2C—the discretionary draw consolidated and centered around 2:00 pm.

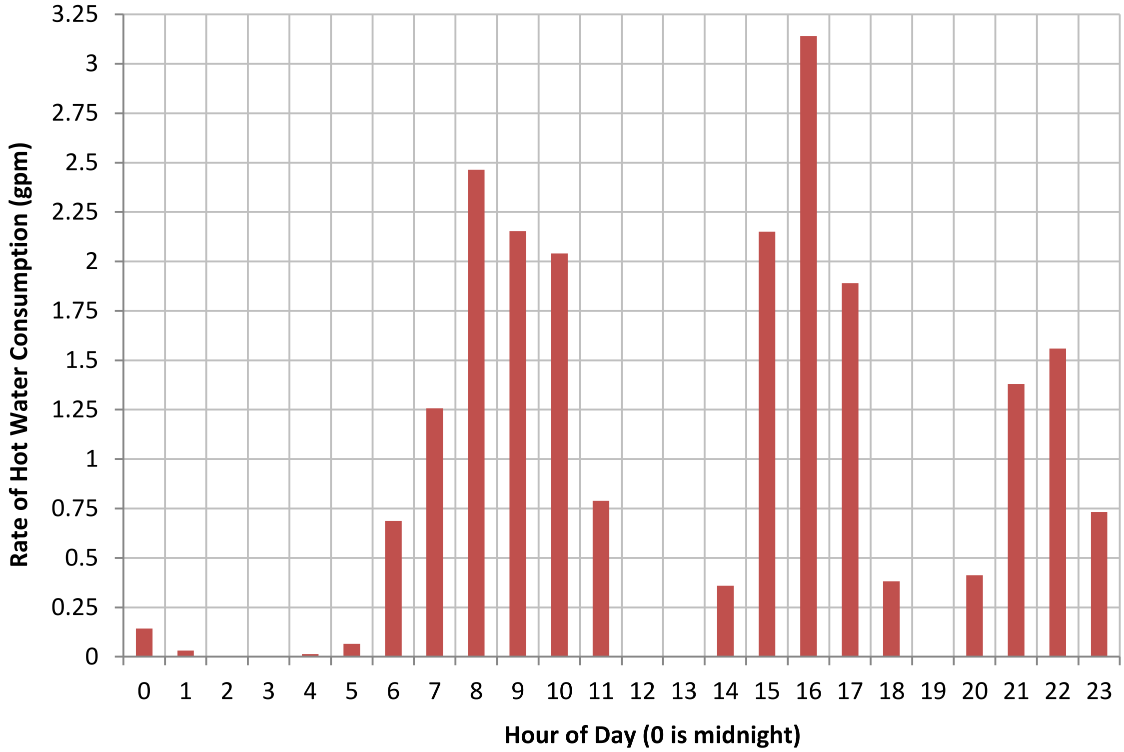

*Figure 57***.** Profile 2D—the discretionary draw consolidated and centered around 4:00 pm.

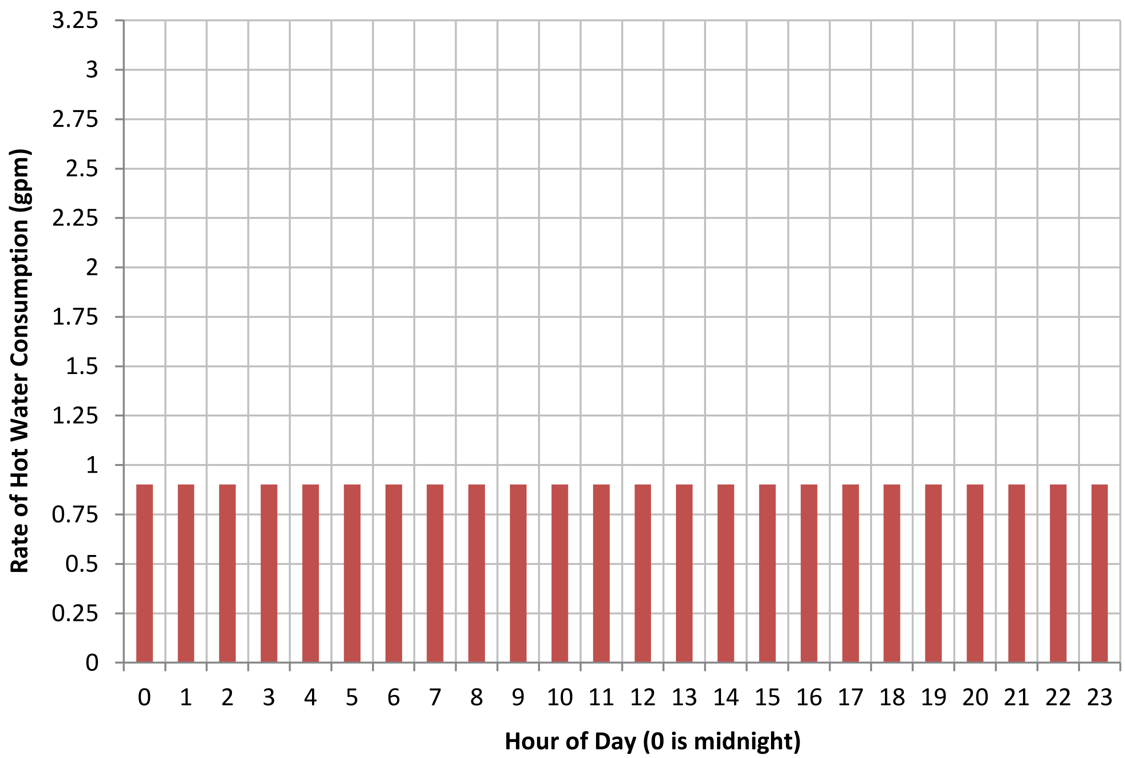

*Figure 58***.** Profile 2E—constant draw throughout the day.

Table 4.

Summary of Hot Water Draw Profiles for Hotel #2

Profile	Description
2A	measured from data
2B	discretionary draw moved to morning
2C	discretionary draw centered at 2:00 pm
2D	discretionary draw centered at 4:00 pm
2E	constant draw throughout the day

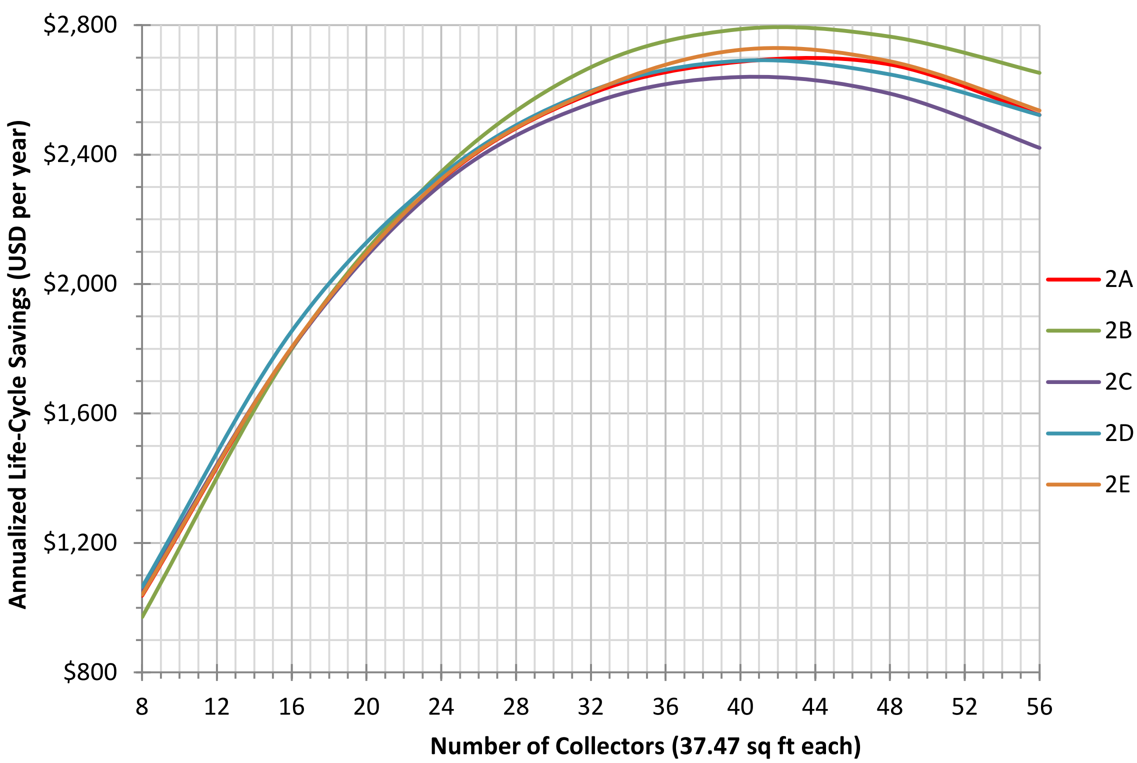

*Figure 59***.** ALCS for each Hotel #2 draw profile as a function of collector area.

The profile with the discretionary draw moved to the morning time (Profile 2B) yields an ALCS 3.75% higher than that for the measured draw profile (Profile 2A). The optimal number of 4-by-10 foot collectors is 42 (1498.8 ft^2). The corresponding optimal collector flow rate is 42 gpm (0.98 gpm/ft^2 collector area), and the optimal storage volume is 6000 gal. The system will save $53,800 over its 20 years and will pay for itself in 4.67 years.

CHAPTER 6

CONCLUSIONS

Correlation of Occupancy and Hot Water Consumption

No correlation was found between hotel occupancy and hotel hot water consumption. Hotel occupancy should not be used to predict hot water consumption.

SDHW System Optimization

Collector Title Angle

The optimal tilt angle is 33 from horizontal for Hotel #1 and 34 from horizontal for Hotel #2, which is consistent with common tilt angle recommendations for sites at Boone's latitude. In each case, the difference in life-cycle savings between a tilt angle of 33 and 34 is less than 0.05%.

Collector Flow Rate

For both hotels, the optimal flow rate was found to be a function of collector area. A significant difference in optimal flow rate was found for each hotel. Figure 60 shows the optimal FA:CA curve for both hotels. In both cases, the optimal flow rate per square foot of collector area decreases as the collector area increases. The optimal flow rates for Hotel #1 and Hotel #2 are 1 and 1.5 gpm per collector, respectively, which is in line with typical flow rates for residential SDHW systems. However, if a smaller collector area is chosen, the flow rate should be increased accordingly. The recommended residential system flow rate is for an optimal collector area (about two collectors), which is what is usually installed. In a larger system, there is more opportunity for error. It is important to determine the optimal system parameters in order to maximize life-cycle savings.

Hotel #1 requires a higher flow rate because it uses more hot water in the morning, before the SDHW is very active. Thus, the storage tank begins at a lower temperature and can accommodate a higher flow rate, which causes a lower collector outlet temperature. Hotel #2 does not use as much hot water before noon, so it begins with the storage tank at a slightly higher temperature. Thus, to maximize performance, it requires a lower flow rate to increase the collector outlet temperature and therefore increase the difference in temperature between the heat transfer fluid and the storage tank.

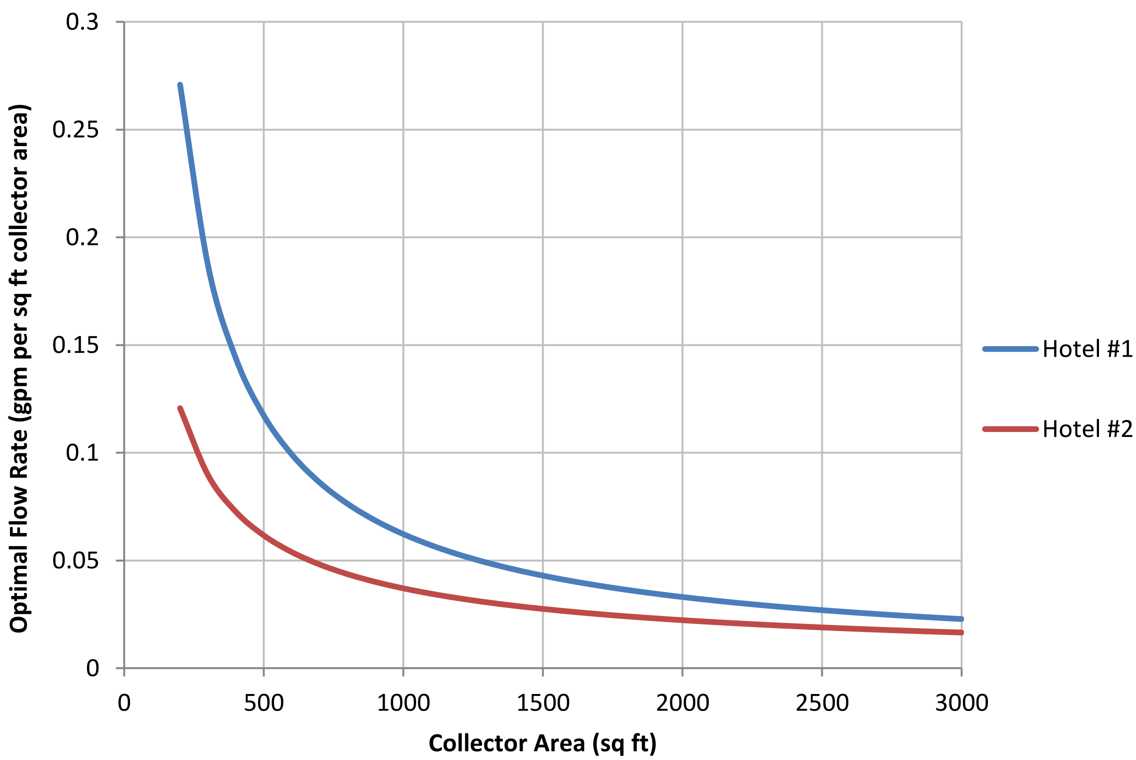

*Figure 60***.** Optimal flow rate, in gpm per sq ft collector area, for both hotels.

Storage Volume

The ideal storage volume for both hotels is around four gallons per square foot of collector area. In both cases, three gallons per square foot of collector area would be acceptable in most cases. This SV:CA ratio is much higher than the typically-recommended 1.5 gallons per square foot of collector area for residential systems.

Effect of Hot Water Draw Profile on SDHW Performance

Hotel #1 and Hotel #2 have similar hot water draw profiles. They both have a large peak of use in the morning, around 8:30 am, a smaller peak in the evening, For both Hotel #1 and Hotel #2, the hot water draw profile was optimized by shifting the discretionary draw to morning hours. However, the effect of this shift on the life-cycle savings is small (2.7% for Hotel #1 and 3.75% for Hotel #2).

Presumably, the effect of shifting the hot water draw profile would be more pronounced if the storage tank were not sized properly. A storage tank that is sized properly for the measured draw profile at each hotel is large enough to accommodate even drastic changes in hot water usage patterns with little impact on SDHW system performance.

Recommendations for Further Research

Hotel hot water consumption should be monitored for at least one year. It is possible that a correlation between occupancy and hot water consumption could manifest itself with a larger data set. More information about hot water uses at hotels should be obtained, and other correlations should be attempted. It is not practical to need to measure hot water consumption in order to size a water heating system. The tank outlet flow rate, recirculation loop flow rate, and the the flow rate and temperature of water exiting the mixing valve should be measured as well.

The effects of the following SDHW parameters on system performance in hotels should be investigated: heat exchanger surface area, storage tank stratification, pipe diameter and length, and variable speed pumps.

REFERENCES

American Water Heaters. (2009). *Motel / hotel sizing*. Retrieved from http://www.americanwaterheatersizing.com/ApplicationData/HotelMotel.aspx

AO Smith Corporation. (2009). *Motel / hotel sizing*. Retrieved from http://www.hotwatersizing.com/ApplicationData/HotelMotel.aspx

Arias, D.A., McMahan, A.C., & Klein, S.A. (2008). Sensitivity of long-term performance simulations of solar energy systems to the degree of stratification in the thermal storage unit. *International Journal of Energy Research*, *32*, 242-254.

American Society of Heating, Refrigerating, and Air-conditioning Engineers (ASHRAE). (1988). *Active solar heating systems design manual*. Retrieved from http://www.solar-rating.org/commercial/documents/designmanual/ASHRAEDesignManualIntro.pdf

Carpenter, S.C., & Kokko, J.P. (1988). Estimating hot water use in existing commercial buildings. *ASHRAE Transactions*, *94* (2).

Cristofari, C., Notton, G., Poggi, P., & Louche, A. (2003). Influence of the flow rate and the tank stratification degree on the performances of a solar flat-plate collector. *International Journal of Thermal Sciences*, *42* (5), 455-469.

Database of State Incentives for Renewable Energy (DSIRE). (2007a). *Business Energy Investment Tax Credit (ITC).* Retrieved from http://www.dsireusa.org/library/includes/incentive2.cfm?Incentive_Code=US02F&State=federal&currentpageid=1&ee=1&re=1

Database of State Incentives for Renewable Energy (DSIRE). (2007b). *Renewable Energy Tax Credit (Corporate).* Retrieved fromhttp://www.dsireusa.org/library/includes/incentive2.cfm?Incentive_Code=NC19F&state=NC&CurrentPageID=1&RE=1&EE=1

Database of State Incentives for Renewable Energy (DSIRE). (2010). *Modified Accelerated Cost-Recovery System (MACRS) + Bonus Depreciation (2008-2012).* Retrieved from http://www.dsireusa.org/incentives/incentive.cfm?Incentive_Code=US06F

Department of Energy. (1981). Summary report of energy usage/consumption analysis for six hotels/motels. *DOE/CS/20376—1*.

Department of Justice. (2007, October 25). *British petroleum to pay more than $370 million in environmental crimes, fraud cases*. Retrieved from http://www.justice.gov/opa/pr/2007/October/07_ag_850.html

Department of the Treasury, Internal Revenue Service. (2010). *Instructions for form 1120: U.S. corporate income tax return.* Retrieved from http://www.irs.gove/pub/irs-pdf/i1120.pdf

Duke Energy. (2010). *Duke Energy Carolinas Standard Purchase Offer for Renewable Energy Certificates ("RECs").* Retrieved from http://extwebqa.duke-energy.com/pdfs/REC-Purchase-Offer-Info.pdf

Energy Information Administration. (2006). *Water-heating energy sources, number of buildings for non-mall buildings, 2003*. Retrieved from http://www.eia.doe.gov/emeu/cbecs/cbecs2003/detailed_tables_2003/2003set6/2003html/b31.html

Energy Information Administration. (2008a). *Commercial buildings energy consumption survey: Table B31, Water heating energy sources, number of buildings for non-mall buildings.* Retrieved from http://www.eia.doe.gov/emeu/cbecs/cbecs2003/detailed_tables_2003/detailed_tables_2003.html

Energy Information Administration. (2008b). *Commercial buildings energy consumption survey: Table E1A, Major fuel consumption by end use for all buildings*. Retrieved from http://www.eia.doe.gov/emeu/cbecs/cbecs2003/detailed_tables_2003/detailed_tables_2003.html

Energy Information Administration. (2010a). Annual solar thermal collector domestic shipments. Retrieved from http://www.eia.doe.gov/cneaf/solar.renewables/page/solarreport/table2_2.html

Energy Information Administration. (2010b). *Average yearly North Carolina commercial price of electricity (cents per kilowatt-hour).* Retrieved from http://www.eia.doe.gov/cneaf/electricity/epa/epa_sprdshts.html

Energy Information Administration. (2010c). *Notes and sources: Data*. Retrieved from http://www.eia.doe.gov/state/NotesSources_Data.cfm

Energy Information Administration. (2010d). *Petroleum navigator.* Retrieved from http://www.eia.doe.gov/dnav/pet/hist/LeafHandler.ashx?n=PET&s=WTOTUSA&f=W

Energy Information Administration. (2011c). *2011 Monthly energy review: Appendix A1: British thermal unit conversion factors*. Retrieved from http://www.eia.gov/mer/append_a.html

Energy Information Administration. (2011d). *Monthly North Carolina price of natural gas sold to commercial consumers (dollars per thousand cubic feet).* Retrieved from http://www.eia.doe.gov/dnav/ng/hist/n3020nc3m.htm

Energy Information Administration. (2011e). *Weekly North Carolina no. 2 heating oil wholesale/resale price (dollars per gallon)*. Retrieved from http://www.eia.gov/dnav/pet/hist/LeafHandler.ashx?n=PET&s=W_EPD2F_PWR_SNC_DPG&f=W

Energy Information Administration. (2011f). *Weekly North Carolina propane wholesale/resale price.* Retrieved from http://tonto.eia.doe.gov/dnav/pet/hist/LeafHandler.ashx?n=PET&s=WPRWS204&f=W

Fairey, P., & Parker, D. (2004). A review of hot water draw profiles used in performance analysis of residential domestic hot water systems. *Florida Solar Energy Center*. Retrieved from http://www.fsec.ucf.edu/en/publications/pdf/FSEC-RR-56-04.pdf

German Solar Energy Society. (2006). *Planning and installing solar thermal systems: A guide for installers, architects and engineers*. London: James & James.

Hasek, G. (2008, January 8). Confederation Place Owners Hot on Trail of Solar Technologies. *Green Lodging News*. Retrieved from http://www.greenlodgingnews.com/Content.aspx?id=1728

Hasek, G. (2009, March). Future Looks Brighter for Solar Hot Water Heating Systems at Hotels. *Green Lodging News*. Retrieved from http://www.greenerbuildings.com/feature/2009/03/18/solar-hot-water-heating-hotels?page=0%2C0

Jordan, U., & Furbo, S. (2005). Thermal stratification in small solar domestic storage tanks caused by draw-offs. *Solar Energy*. *78*(2), 291-300.

Jordan, U., & Vajen, K. (2001). Influence of the DHW load profile on the fractional energy savings: A case study of a solar combi-system with TRNSYS simulations. *Solar Energy*. *69* (Suppl.). Nos. 1-6, 197-208.

Kerkeni, C., BenJemaa, F., Kooli, S., Farhat, A., & Belghith, A. (2000). Solar domestic hot water: numerical and experimental study of the thermal stratification in a storage tank. *2000 Mediterranean Conference for Environment and Solar*. 195-199.

Knudsen, S. (2002). Consumers' influence on the thermal performance of small SDHW systems—Theoretical investigations. *Solar Energy*. *73* (1), 33-42.

Kulkarni, G.N., Kedare, S.B., & Bandyopadhyay, S. (2007). Determination of design space and optimization of solar water heating systems. *Solar Energy*. *81*, 958-968.

Loutzenhiser, P.G., Manz, H., Felsmann, C., Strachan, P.A., Frank, T., & Maxwell, G.M. (2007). Empirical validation of models to compute solar irradiance on inclined surfaces for building energy simulation. *Solar Energy, 81*, 254-267.

Michaelides, I.M., & Wilson, D.R. (1996). Optimum design criteria for solar hot water systems. *Renewable Energy, 9* (1-4), 649-652.

National Renewable Energy Laboratory (NREL). (2003, December). *A consumer guide: heat your water with the sun.* For the US Department of Energy's Office of Energy Efficiency and Renewable Energy. Retrieved from http://www.nrel.gov/docs/fy04osti/34279

Ndoye, B., & Sarr, M. (2008). Analysis of domestic hot water energy consumption in large buildings under standard conditions in Senegal. *Building and Environment*. *43*, 1216-1224.

Novan to Install. (2008, November). *Novan to install one of nation's largest solar hot water systems for hotels at the Hyatt Regency Scottsdale Resort and Spa*. Elite Meetings. Retrieved from http://www.elitemeetings.com/property/hyatt-regency-scottsdale-resort-and-spa-at-gainey-ranch/

Pillai, I., & Banerjee, R. (2004). Impact of hot water usage pattern and location on economics of solar water heating systems. *Water and Energy Abstracts*, *14*(4). Retrieved from http://www.me.iitb.ac.in/~rangan/publications/recent papers published_homepage/solar paper.pdf

Pillai, I., & Banerjee, R. (2007). Methodology for estimation of potential for solar water heating in a target area. *Solar Energy*, *81*(2), 162-172.

Racine, W.C., & Campillo, C.J. (1986). Characteristics of instrumented sites for the on-site fuel cell field test project. *Science Applications International Corp.*, *Report No. SAIC-86/1929, Gas Research Institute Report No. GRI-86/0292*.

Rankin, R., & Rousseau, P.G. (2006). Sanitary hot water consumption patterns in commercial and industrial sectors in South Africa: Impact on heating system design. *Energy Conversion & Management*. *47*, 687-701.

Reddy, T.A. (2007). Active solar heating systems. In F. Kreith & R. Mahajan, (Eds.), *Handbook of energy efficiency and renewable energy* (Ch. 20, pp. 1-48). London: Taylor & Francis Group, LLC.

Renewable Energy World. (2010, July). *State RPS' Lead to 250% Market Growth by 2025*. Retrieved from http://www.renewableenergyworld.com/rea/news/article/2010/07/state-rps-lead-to-250-market-growth-by-2025

Russo, B.J., & Chvala, W.D. (2010). US Department of Energy, Pacific Northwest National Laboratory. *Solar hot water application assessment for u.s. army imcom-southeast region* (PNNL-19811)

Saefong, M.P. (2010, May 28). Shale's a curse and blessing for natural gas . *Market Watch*. Retrieved from http://www.marketwatch.com/story/shales-a-curse-and-blessing-for-natural-gas-2010-05-28

Shah, L., & Furbo, S. (2003). Entrance effects in solar storage tanks. *Solar Energy*. *1*(4), 337-348.

Sharp, M.K., & Loehrke, R.I. (1979). Stratified thermal storage in residential solar energy applications. *Journal of Energy, 3*(2), doi: 79-4075.

Solar Energy Laboratory. (2006). TRNSYS 16 Documentation (included with software)

Solar Rating and Certification Corporation. (2010). *SRCC home Page*. Retrieved from http://www.solar-rating.org/

State Water Heaters. (2009). *Motel / hotel sizing*. Retrieved from http://www.statewaterheatersizing.com/ApplicationData/HotelMotel.aspx

Thermal Energy System Specialists. (2009). *TRNSYS*. Retrieved from http://www.trnsys.com/

Thermal Energy System Specialists (n.d.). Type534: Vertically cylindrical storage tank with immersed heat exchanger. Component documentation (included with software).

Thrasher, W.H., & DeWerth, D.W. (1993). Comparison of collected and compiled existing data on service hot water use patterns in residential and commercial establishments: Phase II final report. For ASHRAE, research project no. 600-RP.

Thrasher, W.H., DeWerth, D.W., & Becker, B.R. (1990). Comparison of collected and compiled existing data on service hot water use patterns in residential and commercial establishments: Phase I final report. For ASHRAE, research project no. 600-RP.

United States Bureau of Labor Statistics. (2011). *Focus on prices and spending: Consumer price index: Fourth quarter 2010.* Retrieved from http://www.bls.gov/opub/focus/volume1_nmber 15/cpi_1_15.pdf

Werden, R.G., & Spielvogel, L.G. (1969). Sizing of service water heating equipment in commercial and institutional buildings. *R.G. Werden Associates, Inc. Report No. 2 for Edison Electric Institute.*

APPENDIX A

HOTEL HOT WATER USE QUESTIONNAIRE

Basic information:
What is the square footage of this hotel?
How many rooms are there in this hotel?
How many people typically stay in each room?

Laundry:
When is laundry typically done?
How many loads are typically done per day?
How many washing machines are usually run at the same time?
Does this hotel offer personal laundry services to guests?

Kitchen:
What times during the day is the kitchen used?
What is the kitchen used for?
For how long is the kitchen used each time?

Pool/hot tubs:
What type of fuel is used to heat the pool?
Does this hotel have any hot tubs and/or “garden tubs”? How many?

Miscellaneous:
What temperature do you usually keep the water heaters (or boilers) set at?
Does this hotel have low-flow shower heads installed, or any other water-saving devices?

Bills and history:
If possible, please attach the following:

- Daily hotel occupancy for this hotel, June 1 – June 18
- Occupancy for the past year for this hotel
- Monthly water bills for the past year for this hotel
- Monthly propane bills for the past year for this hotel

APPENDIX B

TRNSYS INPUT FILE (DECK) AND STORAGE TANK TEXT FILES

```
VERSION 16.1
*******************************************************************************
*** TRNSYS input file (deck) generated by TrnsysStudio
*** on Monday, April 25, 2011 at 00:47
*** from TrnsysStudio project: C:\Users\Eric\Desktop\TRNSYSmodeling\Hotel1.tpf
***
*** If you edit this file, use the File/Import TRNSYS Input File function in
*** TrnsysStudio to update the project.
***
*** If you have problems, questions or suggestions please contact your local
*** TRNSYS distributor or mailto:software@cstb.fr
***
*******************************************************************************


*******************************************************************************
*** Units
*******************************************************************************

*******************************************************************************
*** Control cards
*******************************************************************************
* START, STOP and STEP
CONSTANTS 3
START=0
STOP=8760.000229455
STEP=0.999999972
* User defined CONSTANTS

*                          SIMULATION Start time  End time       Time step
SIMULATION    START  STOP    STEP
*                          Integration        Convergence
TOLERANCES 0.001 0.001
*                          Max iterations     Max warnings     Trace limit
LIMITS 30 2000 30
*                          TRNSYS numerical integration solver method
DFQ 1
*                          TRNSYS output file width, number of characters
WIDTH 80
*                          NOLIST statement
LIST
*                          MAP statement
MAP
*                          Solver statement  Minimum relaxation factor        Maximum
relaxation factor
SOLVER 0 1 1
```

```
*                                       DEBUG statement
NAN_CHECK 0
OVERWRITE_CHECK 0
TIME_REPORT 0
*                                       EQUATION SOLVER statement
EQSOLVER 1

* Model "Type2b" (Type 2)
*

UNIT 6 TYPE 2   Type2b
*$UNIT_NAME Type2b
*$MODEL .\Controllers\Differential Controller w_ Hysteresis\for Temperatures\Solver 0 (Successive
Substitution) Control Strategy\Type2b.tmf
*$POSITION 189 197
*$LAYER Outputs #
*$# NOTE: This control strategy can only be used with solver 0 (Successive substitution)
*$#
PARAMETERS 2
* 1 No. of oscillations
5
* 2 High limit cut-out
90
INPUTS 6
* Collectors:Outlet temperature ->Upper input temperature Th
3,1
* Type534:Tank nodal temperature-6 ->Lower input temperature Tl
25,20
* Type534:Average tank temperature ->Monitoring temperature Tin
25,3
* Type2b:Output control function ->Input control function
6,1
* [unconnected] Upper dead band dT
0,0
* [unconnected] Lower dead band dT
0,0
*** INITIAL INPUT VALUES
20 20 20 0 10 2
*------------------------------------------------------------------------------

* Model "Type8" (Type 8)
*

UNIT 31 TYPE 8  Type8
*$UNIT_NAME Type8
*$MODEL .\Controllers\3-Stage Room Thermostat\Type8.tmf
*$POSITION 965 495
*$LAYER Weather - Data Files #
PARAMETERS 6
* 1 Nb. of oscillations permitted
5
* 2 1st stage heating in 2nd stage?
1
* 3 Minimum primary source temperature
-20
* 4 Temperature for cooling
```

```
100
* 5 1st stage heating temperature
49.777799
* 6 2nd stage heating temperature
-20
INPUTS 2
* [unconnected] Room temperature
0,0
* [unconnected] 1st stage source temperature
0,0
*** INITIAL INPUT VALUES
30.87 30
*------------------------------------------------------------------------------

* EQUATIONS "Time of day"
*
EQUATIONS 1
TimeOfDay = mod(time,24)
*$UNIT_NAME Time of day
*$LAYER Main
*$POSITION 82 399

*------------------------------------------------------------------------------


* Model "Type62" (Type 62)
*

UNIT 33 TYPE 62          Type62
*$UNIT_NAME Type62
*$MODEL .\Utility\Calling External Programs\Excel\Type62.tmf
*$POSITION 220 421
*$LAYER Main #
PARAMETERS 4
* 1 Mode
0
* 2 Nb of inputs
1
* 3 Nb of outputs
1
* 4 Show Excel
0
INPUTS 1
* Time of day:TimeOfDay ->input
TimeOfDay
*** INITIAL INPUT VALUES
0
LABELS 1
"C:\Users\Eric\Desktop\TRNSYSmodeling\Profiles\NewLaquinta 60-min - modified-4.xls"
*------------------------------------------------------------------------------

* EQUATIONS "Daily load"
*
EQUATIONS 3
mdDHW = [33,1]  * 8.34 / 2.205 * 60   ! Multiply by daily consumption, kg
TCold = 20.067
```

```
gpm = [33,1]
*$UNIT_NAME Daily load
*$LAYER Outputs
*$POSITION 301 425

*------------------------------------------------------------------------------


* EQUATIONS "Energy rate"
*
EQUATIONS 1
HeatSource_NRG_rate = [3,3] + [24,3]
*$UNIT_NAME Energy rate
*$LAYER Main
*$POSITION 380 250

*------------------------------------------------------------------------------


* Model "Pump-2" (Type 3)
*

UNIT 32 TYPE 3 Pump-2
*$UNIT_NAME Pump-2
*$MODEL .\Hydronics\Pumps\Single Speed\Type3b.tmf
*$POSITION 969 399
*$LAYER Main #
PARAMETERS 5
* 1 Maximum flow rate
10000
* 2 Fluid specific heat
4.19
* 3 Maximum power
1000
* 4 Conversion coefficient
0.05
* 5 Power coefficient
0.5
INPUTS 3
* Type534-3:Temperature at HX Outlet ->Inlet fluid temperature
29,21
* Type534-3:HX flow rate ->Inlet mass flow rate
29,22
* Type8:Control signal for 1st stage heating ->Control signal
31,1
*** INITIAL INPUT VALUES
20 100 1
*------------------------------------------------------------------------------

* Model "Pump" (Type 3)
*

UNIT 4 TYPE 3   Pump
*$UNIT_NAME Pump
*$MODEL .\Hydronics\Pumps\Single Speed\Type3b.tmf
*$POSITION 140 148
```

```
*$LAYER Main #
PARAMETERS 5
* 1 Maximum flow rate
15052.31832
* 2 Fluid specific heat
4.19
* 3 Maximum power
1079.999971
* 4 Conversion coefficient
0.05
* 5 Power coefficient
1
INPUTS 3
* Type31:Outlet temperature ->Inlet fluid temperature
36,1
* Type31:Outlet flow rate ->Inlet mass flow rate
36,2
* Type2b:Output control function ->Control signal
6,1
*** INITIAL INPUT VALUES
20 100 1
*------------------------------------------------------------------------------

* Model "Weather" (Type 109)
*

UNIT 2 TYPE 109	 Weather
*$UNIT_NAME Weather
*$MODEL .\Weather Data Reading and Processing\Standard Format\TMY2\Type109-TMY2.tmf
*$POSITION 105 23
*$LAYER Water Loop #
PARAMETERS 4
* 1 Data Reader Mode
2
* 2 Logical unit
108
* 3 Sky model for diffuse radiation
4
* 4 Tracking mode
1
INPUTS 3
* [unconnected] Ground reflectance
0,0
* [unconnected] Slope of surface
0,0
* [unconnected] Azimuth of surface
0,0
*** INITIAL INPUT VALUES
0.2 33 0
*** External files
ASSIGN "C:\Program Files\Trnsys16_1\Weather\US-TMY2\US-TN-Bristol-13877.tm2" 108
*|? Weather data file |1000
*------------------------------------------------------------------------------

* Model "Collectors" (Type 1)
*
```

```
UNIT 3 TYPE 1   Collectors
*$UNIT_NAME Collectors
*$MODEL .\Solar Thermal Collectors\Quadratic Efficiency Collector\2nd-Order Incidence Angle
Modifiers\Type1b.tmf
*$POSITION 301 137
*$LAYER Main #
PARAMETERS 11
* 1 Number in series
1
* 2 Collector area
194.88
* 3 Fluid specific heat
4.19
* 4 Efficiency mode
1
* 5 Tested flow rate
37.869112
* 6 Intercept efficiency
.706
* 7 Efficiency slope
17.675999
* 8 Efficiency curvature
0
* 9 Optical mode 2
2
* 10 1st-order IAM
.194
* 11 2nd-order IAM
.006
INPUTS 9
* Pump:Outlet fluid temperature ->Inlet temperature
4,1
* Pump:Outlet flow rate ->Inlet flowrate
4,2
* Weather:Ambient temperature ->Ambient temperature
2,1
* Weather:total radiation on tilted surface ->Incident radiation
2,18
* Weather:total radiation on horizontal ->Total horizontal radiation
2,12
* Weather:sky diffuse radiation on horizontal ->Horizontal diffuse radiation
2,14
* [unconnected] Ground reflectance
0,0
* Weather:angle of incidence for tilted surface  ->Incidence angle
2,22
* Weather:slope of tilted surface ->Collector slope
2,23
*** INITIAL INPUT VALUES
20 100 10 0 0 0 0.2 45 0
*------------------------------------------------------------------------------

* Model "Type534-3" (Type 534)
*
```

```
UNIT 29 TYPE 534	Type534-3
*$UNIT_NAME Type534-3
*$MODEL .\Storage Tank Library (TESS)\Cylindrical Tank\Vertical Cylinder\Type534.tmf
*$POSITION 825 335
*$LAYER Main #
PARAMETERS 5
* 1 Logical unit for data file
110
* 2 # of tank nodes
6
* 3 Number of ports
1
* 4 Number of immersed heat exchangers
1
* 5 Number of miscellaneous heat flows
0
INPUTS 20
* Type534:Temperature at outlet ->Inlet temperature for port
25,1
* Type534:Flow rate at outlet ->Inlet flow rate for port
25,2
* Type700:Outlet fluid temperature ->Inlet temperature for HX
24,1
* Type700:Outlet fluid flowrate ->Inlet flow rate for HX
24,2
* [unconnected] Top loss temperature
0,0
* [unconnected] Edge loss temperature for node-1
0,0
* [unconnected] Edge loss temperature for node-2
0,0
* [unconnected] Edge loss temperature for node-3
0,0
* [unconnected] Edge loss temperature for node-4
0,0
* [unconnected] Edge loss temperature for node-5
0,0
* [unconnected] Edge loss temperature for node-6
0,0
* [unconnected] Bottom loss temperature
0,0
* [unconnected] Gas flue temperature
0,0
* [unconnected] Inversion mixing flow rate
0,0
* [unconnected] Auxiliary heat input for node-1
0,0
* [unconnected] Auxiliary heat input for node-2
0,0
* [unconnected] Auxiliary heat input for node-3
0,0
* [unconnected] Auxiliary heat input for node-4
0,0
* [unconnected] Auxiliary heat input for node-5
0,0
* [unconnected] Auxiliary heat input for node-6
```

```
0,0
*** INITIAL INPUT VALUES
20 0 20 0 32.019 32.019 32.019 32.019 32.019 32.019 32.019 32.019 32.019
-1 0 0 0 0 0 0
DERIVATIVES 6
* 1 Initial Tank Temperature-1
20.067
* 2 Initial Tank Temperature-2
20.067
* 3 Initial Tank Temperature-3
20.067
* 4 Initial Tank Temperature-4
20.067
* 5 Initial Tank Temperature-5
20.067
* 6 Initial Tank Temperature-6
20.067
*** External files
ASSIGN "C:\Users\Eric\Desktop\TRNSYSmodeling\BoilerFileHotel1.dat" 110
*|? Which file contains the parameter values for this component? |1000
*------------------------------------------------------------------------------

* Model "Type31-2" (Type 31)
*

UNIT 37 TYPE 31          Type31-2
*$UNIT_NAME Type31-2
*$MODEL .\Hydronics\Pipe_Duct\Type31.tmf
*$POSITION 305 236
*$LAYER Main #
PARAMETERS 6
* 1 Inside diameter
0.05715
* 2 Pipe length
45.72
* 3 Loss coefficient
10
* 4 Fluid density
1000
* 5 Fluid specific heat
4.19
* 6 Initial fluid temperature
22.673912
INPUTS 3
* Collectors:Outlet temperature ->Inlet temperature
3,1
* Collectors:Outlet flowrate ->Inlet flow rate
3,2
* [unconnected] Environment temperature
0,0
*** INITIAL INPUT VALUES
10 100 30.869
*------------------------------------------------------------------------------

* Model "Type534" (Type 534)
*
```

UNIT 25 TYPE 534 Type534
*$UNIT_NAME Type534
*$MODEL .\Storage Tank Library (TESS)\Cylindrical Tank\Vertical Cylinder\Type534.tmf
*$POSITION 372 319
*$LAYER Weather / Data Files #
PARAMETERS 5
* 1 Logical unit for data file
109
* 2 # of tank nodes
6
* 3 Number of ports
1
* 4 Number of immersed heat exchangers
1
* 5 Number of miscellaneous heat flows
0
INPUTS 20
* Daily load:TCold ->Inlet temperature for port
TCold
* Daily load:mdDHW ->Inlet flow rate for port
mdDHW
* Type31-2:Outlet temperature ->Inlet temperature for HX
37,1
* Type31-2:Outlet flow rate ->Inlet flow rate for HX
37,2
* [unconnected] Top loss temperature
0,0
* [unconnected] Edge loss temperature for node-1
0,0
* [unconnected] Edge loss temperature for node-2
0,0
* [unconnected] Edge loss temperature for node-3
0,0
* [unconnected] Edge loss temperature for node-4
0,0
* [unconnected] Edge loss temperature for node-5
0,0
* [unconnected] Edge loss temperature for node-6
0,0
* [unconnected] Bottom loss temperature
0,0
* [unconnected] Gas flue temperature
0,0
* [unconnected] Inversion mixing flow rate
0,0
* [unconnected] Auxiliary heat input for node-1
0,0
* [unconnected] Auxiliary heat input for node-2
0,0
* [unconnected] Auxiliary heat input for node-3
0,0
* [unconnected] Auxiliary heat input for node-4
0,0
* [unconnected] Auxiliary heat input for node-5
0,0

* [unconnected] Auxiliary heat input for node-6
0,0
*** INITIAL INPUT VALUES
20 0 20 0 32.019 32.019 32.019 32.019 32.019 32.019 32.019 32.019 32.019
-1 0 0 0 0 0 0
DERIVATIVES 6
* 1 Initial Tank Temperature-1
20.067
* 2 Initial Tank Temperature-2
20.067
* 3 Initial Tank Temperature-3
20.067
* 4 Initial Tank Temperature-4
20.067
* 5 Initial Tank Temperature-5
20.067
* 6 Initial Tank Temperature-6
20.067
*** External files
ASSIGN "C:\Users\Eric\Desktop\TRNSYSmodeling\StorageFileHotel1.dat" 109
*|? Which file contains the parameter values for this component? |1000
*--

* Model "Type31" (Type 31)
*

UNIT 36 TYPE 31 Type31
*$UNIT_NAME Type31
*$MODEL .\Hydronics\Pipe_Duct\Type31.tmf
*$POSITION 145 279
*$LAYER Water Loop #
PARAMETERS 6
* 1 Inside diameter
0.05715
* 2 Pipe length
45.72
* 3 Loss coefficient
10
* 4 Fluid density
1000
* 5 Fluid specific heat
4.19
* 6 Initial fluid temperature
22.673912
INPUTS 3
* Type534:Temperature at HX Outlet ->Inlet temperature
25,21
* Type534:HX flow rate ->Inlet flow rate
25,22
* [unconnected] Environment temperature
0,0
*** INITIAL INPUT VALUES
10 100 30.869
*--

* Model "Tee piece" (Type 11)

```
*

UNIT 12 TYPE 11        Tee piece
*$UNIT_NAME Tee piece
*$MODEL .\Hydronics\Tee-Piece\Other Fluids\Type11h.tmf
*$POSITION 556 222
*$LAYER Main #
PARAMETERS 1
* 1 Tee piece mode
1
INPUTS 4
* Type534-3:Temperature at outlet ->Temperature at inlet 1
29,1
* Type534-3:Flow rate at outlet ->Flow rate at inlet 1
29,2
* Daily load:TCold ->Temperature at inlet 2
TCold
* Daily load:mdDHW ->Flow rate at inlet 2
mdDHW
*** INITIAL INPUT VALUES
20 100 20 100
*------------------------------------------------------------------------------

* Model "Type700" (Type 700)
*

UNIT 24 TYPE 700       Type700
*$UNIT_NAME Type700
*$MODEL .\HVAC Library (TESS)\Boiler\Efficiencies as Inputs\Type700.tmf
*$POSITION 852 442
*$LAYER Outputs #
*$# BOILER
PARAMETERS 2
* 1 Rated Capacity
629868.648627
* 2 Fluid specific heat
4.19
INPUTS 6
* Pump-2:Outlet fluid temperature ->Inlet fluid temperature
32,1
* Pump-2:Outlet flow rate ->Inlet fluid flowrate
32,2
* Type8:Control signal for 1st stage heating ->Input Control Signal
31,1
* [unconnected] Set-point temperature
0,0
* [unconnected] Boiler Efficiency
0,0
* [unconnected] Combustion Efficiency
0,0
*** INITIAL INPUT VALUES
10 0 0 50.000022 0.78 0.85
*------------------------------------------------------------------------------

* EQUATIONS "energy"
*
```

```
EQUATIONS 6
TotalBtuPerStep = SolarBtuPerStep + BoilerBtuPerStep
SolarBtuPerStep = -1*[25,26] * 3.413 /3.6
BoilerBtuPerStep = -1*[29,26]* 3.413/3.6
CollBtuPerStep = [3,3]*3.413 /3.6
ColdPipeBTUperStep = [36,3]* 3.413/3.6
HotPipeBTUperStep = [37,3]* 3.413/3.6
*$UNIT_NAME energy
*$LAYER Main
*$POSITION 585 122

*------------------------------------------------------------------------------


* EQUATIONS "heat flow"
*
EQUATIONS 3
TotalBtuPerHr = SolarBtuPerHr + BoilerBtuPerHr
SolarBtuPerHr = -1*[25,26] * 3.413
BoilerBtuPerHr = -1*[29,26]* 3.413
*$UNIT_NAME heat flow
*$LAYER Outputs
*$POSITION 662 207

*------------------------------------------------------------------------------


* EQUATIONS "Efficiencies"
*
EQUATIONS 4
EtaColl_d = [13,2] / (5*[13,1]+1e-6)
FSol_d = 1 - ( [13,4] / ([13,3] + 1e-6) )
EtaColl = [14,2] / (5*[14,1]+1e-6)
FSol = 1 - ( [14,4] / ([14,3]+ 1e-6) )
*$UNIT_NAME Efficiencies
*$LAYER Weather - Data Files
*$POSITION 231 544

*------------------------------------------------------------------------------


* Model "Daily Integration" (Type 24)
*

UNIT 13 TYPE 24        Daily Integration
*$UNIT_NAME Daily Integration
*$MODEL .\Utility\Integrators\Quantity Integrator\TYPE24.tmf
*$POSITION 91 509
*$LAYER Totals #
PARAMETERS 2
* 1 Integration period
24
* 2 Relative or absolute start time
0
INPUTS 4
* Weather:total radiation on tilted surface ->Input to be integrated-1
```

```
2,18
* Energy rate:HeatSource_NRG_rate ->Input to be integrated-2
HeatSource_NRG_rate
* Type534:Energy delivery rate ->Input to be integrated-3
25,4
* Type534:HX heat transfer rate ->Input to be integrated-4
25,13
*** INITIAL INPUT VALUES
0 0 0 0
*------------------------------------------------------------------------------

* Model "Simulation Integration" (Type 24)
*

UNIT 14 TYPE 24          Simulation Integration
*$UNIT_NAME Simulation Integration
*$MODEL .\Utility\Integrators\Quantity Integrator\TYPE24.tmf
*$POSITION 84 584
*$LAYER Totals #
PARAMETERS 2
* 1 Integration period
STOP
* 2 Relative or absolute start time
0
INPUTS 4
* Weather:total radiation on tilted surface ->Input to be integrated-1
2,18
* Energy rate:HeatSource_NRG_rate ->Input to be integrated-2
HeatSource_NRG_rate
* Type534:Energy delivery rate ->Input to be integrated-3
25,4
* Type534:HX heat transfer rate ->Input to be integrated-4
25,13
*** INITIAL INPUT VALUES
0 0 0 0
*------------------------------------------------------------------------------

* EQUATIONS "energy-2"
*
EQUATIONS 1
gallonsPerHr = [29,2] * 2.205 / 8.34
*$UNIT_NAME energy-2
*$LAYER Main
*$POSITION 1093 282

*------------------------------------------------------------------------------


* Model "total Btu's gained" (Type 24)
*

UNIT 22 TYPE 24          total Btu's gained
*$UNIT_NAME total Btu's gained
*$MODEL .\Utility\Integrators\Quantity Integrator\TYPE24.tmf
*$POSITION 742 142
*$LAYER Outputs #
```

```
PARAMETERS 2
* 1 Integration period
STOP
* 2 Relative or absolute start time
0
INPUTS 4
* energy:TotalBtuPerStep ->Input to be integrated-1
TotalBtuPerStep
* energy:SolarBtuPerStep ->Input to be integrated-2
SolarBtuPerStep
* energy:BoilerBtuPerStep ->Input to be integrated-3
BoilerBtuPerStep
* energy-2:gallonsPerHr ->Input to be integrated-4
gallonsPerHr
*** INITIAL INPUT VALUES
0 0 0 0
*------------------------------------------------------------------------------

* Model "Plotter 1" (Type 65)
*

UNIT 5 TYPE 65 Plotter 1
*$UNIT_NAME Plotter 1
*$MODEL .\Output\Online Plotter\Online Plotter With File\No Units\Type65c.tmf
*$POSITION 553 37
*$LAYER Outputs #
PARAMETERS 12
* 1 Nb. of left-axis variables
2
* 2 Nb. of right-axis variables
2
* 3 Left axis minimum
0
* 4 Left axis maximum
150
* 5 Right axis minimum
0
* 6 Right axis maximum
5000
* 7 Number of plots per simulation
1
* 8 X-axis gridpoints
7
* 9 Shut off Online w/o removing
0
* 10 Logical Unit for output file
106
* 11 Output file units
0
* 12 Output file delimiter
0
INPUTS 4
* Pump:Outlet fluid temperature ->Left axis variable-1
4,1
* Collectors:Outlet temperature ->Left axis variable-2
3,1
```

```
* Weather:total radiation on tilted surface ->Right axis variable-1
2,18
* Collectors:Outlet flowrate ->Right axis variable-2
3,2
*** INITIAL INPUT VALUES
TiColl ToColl GColl mdColl
LABELS  3
"Temperatures"
"Heat transfer rates"
"Weather - Solar Loop"
*** External files
ASSIGN "***.plt" 106
*|? What file should the online print to? |1000
*------------------------------------------------------------------------------

* Model "save Btu's to file" (Type 65)
*

UNIT 21 TYPE 65          save Btu's to file
*$UNIT_NAME save Btu's to file
*$MODEL .\Output\Online Plotter\Online Plotter With File\No Units\Type65c.tmf
*$POSITION 865 142
*$LAYER Main #
PARAMETERS 12
* 1 Nb. of left-axis variables
10
* 2 Nb. of right-axis variables
10
* 3 Left axis minimum
0
* 4 Left axis maximum
100000
* 5 Right axis minimum
0
* 6 Right axis maximum
1000
* 7 Number of plots per simulation
1
* 8 X-axis gridpoints
12
* 9 Shut off Online w/o removing
0
* 10 Logical Unit for output file
113
* 11 Output file units
0
* 12 Output file delimiter
0
INPUTS 20
* total Btu's gained:Result of integration-1 ->Left axis variable-1
22,1
* total Btu's gained:Result of integration-2 ->Left axis variable-2
22,2
* total Btu's gained:Result of integration-3 ->Left axis variable-3
22,3
* total Btu's gained:Result of integration-4 ->Left axis variable-4
```

```
22,4
* Daily load:TCold ->Left axis variable-5
TCold
* Type534-3:Temperature at outlet ->Left axis variable-6
29,1
* Daily load:TCold ->Left axis variable-7
TCold
* Type534:Temperature at outlet ->Left axis variable-8
25,1
* Daily load:gpm ->Left axis variable-9
gpm
* Pump:Power consumption ->Left axis variable-10
4,3
* [unconnected] Right axis variable-1
0,0
* [unconnected] Right axis variable-2
0,0
* [unconnected] Right axis variable-3
0,0
* Collectors:Outlet temperature ->Right axis variable-4
3,1
* energy:SolarBtuPerStep ->Right axis variable-5
SolarBtuPerStep
* energy:BoilerBtuPerStep ->Right axis variable-6
BoilerBtuPerStep
* energy:TotalBtuPerStep ->Right axis variable-7
TotalBtuPerStep
* energy:CollBtuPerStep ->Right axis variable-8
CollBtuPerStep
* energy:ColdPipeBTUperStep ->Right axis variable-9
ColdPipeBTUperStep
* energy:HotPipeBTUperStep ->Right axis variable-10
HotPipeBTUperStep
*** INITIAL INPUT VALUES
TotalBtu SolarBtu BoilerBtu gallons coldTemp hotTemp SolarColdT SolarHotT
gpm pumpKJpHR label label label collTemp SolBTUpHR BoilerBTUpHR TotalBTUpHR
collectorEnergyGain ColdPipeLoss HotPipeLoss
LABELS  3
"Btu"
" "
"total_Btu"
*** External files
ASSIGN "Results\TotalBtu.plt" 113
*|? What file should the online print to? |1000
*------------------------------------------------------------------------------

* Model "save Btu/Hr to file" (Type 65)
*

UNIT 28 TYPE 65          save Btu/Hr to file
*$UNIT_NAME save Btu/Hr to file
*$MODEL .\Output\Online Plotter\Online Plotter With File\No Units\Type65c.tmf
*$POSITION 781 207
*$LAYER Main #
PARAMETERS 12
* 1 Nb. of left-axis variables
```

```
3
* 2 Nb. of right-axis variables
0
* 3 Left axis minimum
0
* 4 Left axis maximum
100000
* 5 Right axis minimum
0
* 6 Right axis maximum
1000
* 7 Number of plots per simulation
1
* 8 X-axis gridpoints
12
* 9 Shut off Online w/o removing
0
* 10 Logical Unit for output file
114
* 11 Output file units
0
* 12 Output file delimiter
0
INPUTS 3
* heat flow:TotalBtuPerHr ->Left axis variable-1
TotalBtuPerHr
* heat flow:SolarBtuPerHr ->Left axis variable-2
SolarBtuPerHr
* heat flow:BoilerBtuPerHr ->Left axis variable-3
BoilerBtuPerHr
*** INITIAL INPUT VALUES
TotalBtuPerHr SolarBtuPerHr BoilerBtuPerHr
LABELS  3
"Btu/hr"
" "
"BtuPerHr"
*** External files
ASSIGN "Results\BtuPerHr.plt" 114
*|? What file should the online print to? |1000
*------------------------------------------------------------------------------

* Model "Plotter 2" (Type 65)
*

UNIT 8 TYPE 65 Plotter 2
*$UNIT_NAME Plotter 2
*$MODEL .\Output\Online Plotter\Online Plotter With File\No Units\Type65c.tmf
*$POSITION 626 318
*$LAYER Main #
PARAMETERS 12
* 1 Nb. of left-axis variables
8
* 2 Nb. of right-axis variables
4
* 3 Left axis minimum
0
```

```
* 4 Left axis maximum
100
* 5 Right axis minimum
0
* 6 Right axis maximum
10000
* 7 Number of plots per simulation
1
* 8 X-axis gridpoints
7
* 9 Shut off Online w/o removing
0
* 10 Logical Unit for output file
107
* 11 Output file units
0
* 12 Output file delimiter
0
INPUTS 12
* Type534:Tank nodal temperature-1 ->Left axis variable-1
25,15
* Type534:Tank nodal temperature-2 ->Left axis variable-2
25,16
* Type534:Tank nodal temperature-3 ->Left axis variable-3
25,17
* Type534:Tank nodal temperature-4 ->Left axis variable-4
25,18
* Type534:Tank nodal temperature-5 ->Left axis variable-5
25,19
* Type534:Tank nodal temperature-6 ->Left axis variable-6
25,20
* Tee piece:Outlet temperature ->Left axis variable-7
12,1
* Type534:Temperature at outlet ->Left axis variable-8
25,1
* Type700:Fluid energy ->Right axis variable-1
24,3
* Tee piece:Outlet flow rate ->Right axis variable-2
12,2
* [unconnected] Right axis variable-3
0,0
* [unconnected] Right axis variable-4
0,0
*** INITIAL INPUT VALUES
TTop T2 T3 T4 T5 TBottom TDHW SolStoreOut QAux mdDHW mdTank mdByPass
LABELS  3
"Temperatures"
"Heat transfer rates"
"Graph 1"
*** External files
ASSIGN "***.pl2" 107
*|? What file should the online print to? |1000
*------------------------------------------------------------------------------

* Model "Potable Temps" (Type 65)
*
```

```
UNIT 30 TYPE 65          Potable Temps
*$UNIT_NAME Potable Temps
*$MODEL .\Output\Online Plotter\Online Plotter With File\No Units\Type65c.tmf
*$POSITION 613 474
*$LAYER Controls #
PARAMETERS 12
* 1 Nb. of left-axis variables
4
* 2 Nb. of right-axis variables
0
* 3 Left axis minimum
0
* 4 Left axis maximum
100
* 5 Right axis minimum
0
* 6 Right axis maximum
1
* 7 Number of plots per simulation
1
* 8 X-axis gridpoints
7
* 9 Shut off Online w/o removing
0
* 10 Logical Unit for output file
111
* 11 Output file units
0
* 12 Output file delimiter
0
INPUTS 4
* Type534-3:Temperature at outlet ->Left axis variable-1
29,1
* [unconnected] Left axis variable-2
0,0
* Tee piece:Outlet temperature ->Left axis variable-3
12,1
* [unconnected] Left axis variable-4
0,0
*** INITIAL INPUT VALUES
TankOut Ground TeeOut DiverterOut
LABELS  3
"Temperature (C)"

"PotableTemps"
*** External files
ASSIGN "***.plt" 111
*|? What file should the online print to? |1000
*------------------------------------------------------------------------------

* Model "Totals" (Type 25)
*

UNIT 18 TYPE 25          Totals
*$UNIT_NAME Totals
```

```
*$MODEL .\Output\Printer\Unformatted\No Units\Type25c.tmf
*$POSITION 492 581
*$LAYER Main #
PARAMETERS 10
* 1 Printing interval
STOP
* 2 Start time
STOP
* 3 Stop time
STOP
* 4 Logical unit
105
* 5 Units printing mode
0
* 6 Relative or absolute start time
0
* 7 Overwrite or Append
-1
* 8 Print header
-1
* 9 Delimiter
0
* 10 Print labels
1
INPUTS 6
* Simulation Integration:Result of integration-1 ->Input to be printed-1
14,1
* Simulation Integration:Result of integration-2 ->Input to be printed-2
14,2
* Simulation Integration:Result of integration-3 ->Input to be printed-3
14,3
* Simulation Integration:Result of integration-4 ->Input to be printed-4
14,4
* Efficiencies:EtaColl ->Input to be printed-5
EtaColl
* Efficiencies:FSol ->Input to be printed-6
FSol
*** INITIAL INPUT VALUES
IColl QuColl QDHW QAux EtaColl FSol
*** External files
ASSIGN "Results\Totals.txt" 105
*|? Output file for printed results |1000
*------------------------------------------------------------------------------

* Model "Daily Results" (Type 25)
*

UNIT 15 TYPE 25          Daily Results
*$UNIT_NAME Daily Results
*$MODEL .\Output\Printer\Unformatted\No Units\Type25c.tmf
*$POSITION 500 514
*$LAYER Main #
PARAMETERS 10
* 1 Printing interval
24
* 2 Start time
```

```
START
* 3 Stop time
STOP
* 4 Logical unit
112
* 5 Units printing mode
0
* 6 Relative or absolute start time
0
* 7 Overwrite or Append
-1
* 8 Print header
-1
* 9 Delimiter
0
* 10 Print labels
1
INPUTS 6
* Daily Integration:Result of integration-1 ->Input to be printed-1
13,1
* Daily Integration:Result of integration-2 ->Input to be printed-2
13,2
* Daily Integration:Result of integration-3 ->Input to be printed-3
13,3
* Daily Integration:Result of integration-4 ->Input to be printed-4
13,4
* Efficiencies:EtaColl_d ->Input to be printed-5
EtaColl_d
* Efficiencies:FSol_d ->Input to be printed-6
FSol_d
*** INITIAL INPUT VALUES
IColl QuColl QDHW QAux EtaColl_d FSol_d
*** External files
ASSIGN "Results\Daily.txt" 112
*|? Output file for printed results |1000
*------------------------------------------------------------------------------

END
```

Solar Storage Tank Text File: StorageTankHotel1

```
TRNSYS16 TESSLIBS2.0 V1
 6      1      1      0
 31.77202031
 5.449269834
 0
 4.19
 973.1
 2.387
 1.454
 0.00017
 0.12
 0.12
 0.12
 0.12
 0.12
 0.12
 0.12
 0.12
 0.12
 1
 6
 1
 0
 0
 0
 0
 0
 0
 3
 4
 0
 4.19
 973.1
 2.387
 1.454
 1
 0.25
 1
 0
 0.01892
 0.02223
 1422
 56
 1
 0
 0.0002811
```

1
0.025
6
0.25
6
0.25
6
0.25
6
0.25
****
20
0
20
0
32.019
32.019
32.019
32.019
32.019
32.019
32.019
32.019
32.019
-1
0
20.067
0
20.067
0
20.067
0
20.067
0
20.067
0
20.067

Auxiliary Tank Text File: BoilerFileHotel1

```
TRNSYS16 TESSLIBS2.0 V1
 6        1        1        0
 1.35314768
 1.09177
 2
 0
 10
 10
 10
 10
 10
 10
 10
 10
 10
 1
 6
 1
 0
 0
 0
 0
 0
 0
 3
 4
 0
 4.19
 973.1
 2.387
 1.454
 1
 0.6
 1
 0
 0.01892
 0.02223
 142200
 7.62
 1
 0
 0.0002811
 0.5
 0.025
 6
 0.25
```

6
0.25
6
0.25
6
0.25
****
20
0
20
0
32.019
32.019
32.019
32.019
32.019
32.019
32.019
32.019
32.019
-1
0
20.067
0
20.067
0
20.067
0
20.067
0
20.067
0
20.067
0
20.067

VITA

Eric Joseph Urban was born in Strongsville, Ohio, on June 2, 1986. He attended primary and secondary school there and graduated from high school in the spring of 2004. He then enrolled at the University of Dayton, and he was awarded the Bachelor of Science degree in Mechanical Engineering in 2008. He completed his Master of Science in Technology degree with a concentration in Appropriate Technology at Appalachian State University in spring of 2011. While at Appalachian State, he served one term as the Department of Technology's representative to the Graduate Student Association Senate and participated in the Appalachian State University Sustainable Energy Society.