Energy Efficiency Potential of Heat Pump Water Heaters in Commercial Buildings

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ABSTRACT

As energy prices continue to rise and pressures increase to reduce global warming emissions world-wide, renewed interest is being shown in heat pump water heaters' (HPWH) potential for dramatic energy and emissions savings in commercial buildings. HPWHs have long been used as an energy efficient method of pool heating in commercial applications; however data is showing potential for similar success in domestic water heating applications. This application evaluation presents field collected performance data and results from HPWHs installed within commercial buildings in the Southeastern United States to heat the buildings' domestic hot water supply. The potential viability of HPWHs is contingent upon many factors including sizing, installation costs, equipment availability, and utility costs; lessons learned are presented along with a focus on the importance of equipment sizing to efficient operation of commercial HPWHs.

Introduction

Energy prices in all sectors are inevitably going to rise in coming years due to energy production cost increases, increasing demand for energy coupled with increasing climate control regulations, and infrastructure constraints. The buildings we live in and the systems we expect to be present in our buildings help make our comfortable way of life possible: air conditioning, ample lighting, domestic hot water on demand, etc. In residential settings occupants have a vested interest in their energy usage since they are typically responsible for the energy costs; thus, the homeowner becomes responsible for the efficiency of their own building.

However, in the commercial sector the building designer and owner/operator are accountable for the energy usage and energy costs of the building. The commercial end-use sector represents a substantial percentage of energy use in the United States. According to the latest *Annual Energy Review,* the commercial sector uses 19% of total US energy consumption or 18.5 quadrillion BTUs (DOE June 2009). Thus, it is the responsibility of the building designer and owner/operator to ensure the building systems are efficient in order to reduce the building's energy consumption and, as a result, cost. Therefore, as a method of addressing energy issues, stress is being placed on pushing the limits of building efficiency through sustainable building initiatives such as USGBC's Leadership in Energy and Environmental Design (LEED) along with national and local building codes. Substantial energy savings can be expected from implementing efficient energy systems into new and existing commercial buildings in the US.

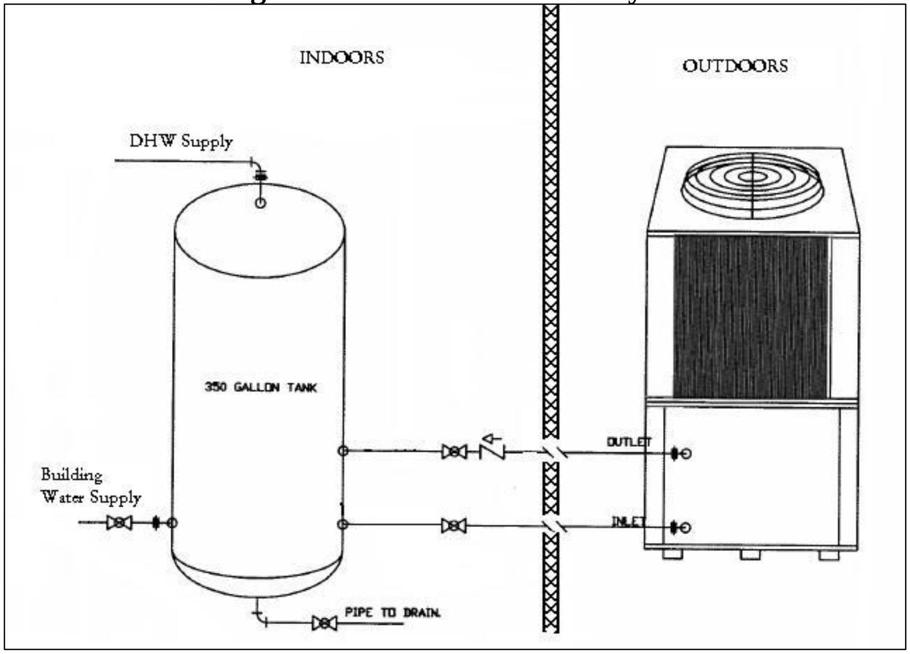
Furthermore, commercial buildings in the US use about 501 trillion Btu for water heating on an annual basis (DOE September 2008). As a result great energy savings potential exists in energy efficient upgrades for domestic hot water (DHW) systems across the US. A technology that is showing great potential for reducing the energy consumption of DWH systems is heat pump water heater (HPWH) systems. HPWHs use a vapor compression refrigeration cycle to move heat from a low temperature source (air, water, or ground) to a higher temperature sink (DHW). HPWHs have been used successfully for heating swimming pools for decades since the required temperature of a pool rarely needs to be above 85°F (EPRI 2007). Additionally, the required heating load for a swimming pool is relatively easily predicted since the volume of water is relatively constant and there are relatively simple equations for calculating the heat loss from a pool based on pool volume, desired temperature, desired temperature pickup, and average temperature of the coldest month (ASHRAE 2007). The idea of using HPWHs for DHW is not new, but years of system vast failures and poor market adoption have forced manufacturers to drop their product lines. Not to mention, the sizing of a HPWH for DHW is complicated by varying heating load due to fluctuating water usage and varying usage patterns of different building types. However, the energy, regulatory, and environmental settings are together shaping the circumstances that make the return of HPWHs in the commercial market attractive and probable. An electric utility in the Southeastern United States has conducted research of HPWHs to demonstrate the technology and work to refine the knowledge needed to properly size and apply HPWHs for domestic water heating in the commercial market. The end goal of this research is to increase market penetration of this technology in the commercial sector by forming rules of thumb for HPWH and storage sizing and convincing manufacturers of the potential of commercial HPWHs for DHW use.

Study Description

This paper will focus on three installations of HPWHs designed to produce DHW for the building on which they were installed. The studies that are described are application-based and are aimed at producing case studies for the HPWH technology as it applies to domestic water heating. Three remote, air-source HPWHs were installed in commercial buildings in the Southeastern US beginning in late 2007 to mid 2009. “Remote” is used to refer to the case where the unit’s evaporator, fan, compressor, and circulating pump are located outdoors and a DHW storage tank is located indoors. Municipal water is supplied directly to the storage tank, and the heat pump is used to heat the water in the tank by circulating the stored water from the tank, through the HPHW, and back to the tank.

These units were installed on buildings with large DHW consumption in an effort to gain insight into the relationship among DHW demand, HPWH size, and storage tank size. A 175,000Btuh (nominal heating capacity as appointed by the manufacturer) unit was installed on an 80 room hotel on the Florida coast with a 350 gallon steel storage tank in late 2007. This unit will be referred to as the “Florida Hotel Unit”. A second 175,000Btuh unit was installed on an 84 room nursing home on the Alabama coast with a 350 gallon steel storage tank in mid-2009. This unit will be referred to the “Alabama Nursing Home Unit”. A 75,000Btuh unit was installed on a 126 room hotel in central Alabama with a 350 gallon steel storage tank. This unit will be referred to as the “Alabama Hotel Unit”. These units were installed in the general arrangement shown in Figure 1. Each of these units served as the primary domestic water heater for the sites; however, each building had a backup heat source for time when the HPWH was unable to run.

Figure 1: General HPWH Layout



Each of these units was instrumented with data collection equipment to collect city inlet water temperature, tank supply temperature to building, DHW consumption, and HPWH energy consumption. The data from these units were collected on at least 15 minute intervals from the time the units were installed through the time of this paper. Selected data will be presented and discussed to show the trended performance of these systems in their respective operating circumstances.

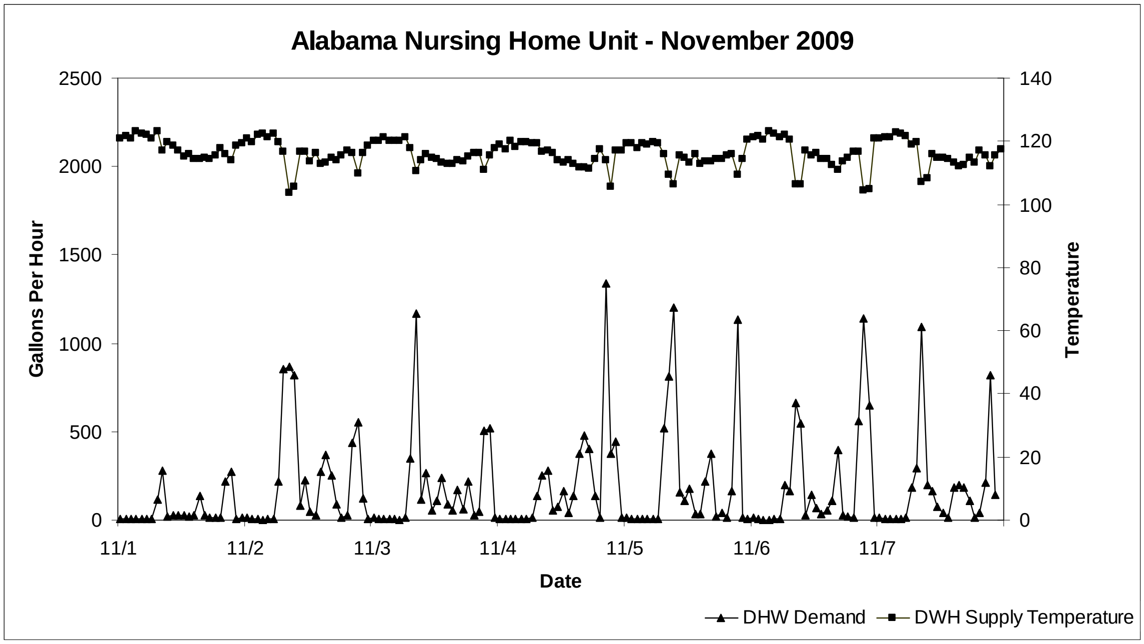
Results

For each site, the data is presented in such a manner as to show how well the unit provides the heating required by the DHW demand. The data includes a trend of the storage tank outlet temperature (labeled "DHW Supply Temperature") and the building's DHW demand. This is followed by a graph of the energy consumption of the HPWH for the same time period. The energy consumption is presented in hourly kWh consumption values. This is intended to convey both the total energy consumed by the HPWH units as well as the average hourly demand of the HPWH: this is important to illustrate the capacity factor of the HPWHs at each site. If a 15ton (nominal) unit is loaded at full capacity for one hour it should use approximately 15 kWh (using the assumption that a typical unit draws approximately 1kW/ton for simplicity). Thus, by looking at the energy consumption on an hourly basis, insight is gained into the capacity factor of each unit: where the capacity factor is the percentage of time the unit runs. As will all compressor-based equipment, the best efficiency and long term reliability is gained when cycling of the compressor is kept at a minimum. Therefore the cycle rate and loading of the system (i.e. capacity factor) is a good indicator of how closely the HPWH is matched to the building's DHW load.

In the interest of succinctness selected trends are presented for each of the three units. November is used to show how the units operate in less than ideal conditions at each site;

however the HPWH is still doing a vast majority of the DHW heating. The first week of November 2009 is show for both of the 175,000Btuh units, whereas the last week of November 2009 had to be shown for the 75,000Btuh unit due to lack of data previous to this date. Summertime data is shown for both of 175,000Btuh units to illustrate nuances in their operation, but none is shown for the 75,000Btuh due to lack of summertime data at time of this paper's creation.

Figure 2: Alabama Nursing Home Unit Nov. '09 Performance



Careful attention should be paid to the comparison between the Alabama Nursing Home unit and the Florida Hotel unit since they are both 175,000Btuh units. It can be seen in Figure 2 that the DHW demand of the building is highly varying and generally peaks around 1100 gallons per hour (gph) once a day and remains below 400gph most other times. Thus, it follows that the storage tank temperature drops well below the 115°F set point only upon these large draws. Other than these brief dips, the HPWH is able to maintain the outlet temperature of the storage tank reasonably well. Furthermore, Figure 3 shows the HPWH is highly loaded.

The DHW demand of the Florida Hotel is considerably lower than that of the Alabama Nursing Home unit; however, they have the same size HPWH. As a result, the Florida Hotel unit is able to maintain the average temperature of the tank around its 115°F set point quite well as shown in Figure 4. However, since the water consumption is so much lower, the unit cycles quite frequently as seen in Figure 5.

If either the Alabama Nursing Home unit or the Florida Hotel unit were operating at full capacity they should draw approximately 12-15kW which would equate to 12-15kWh per hour. The Alabama Nursing Home unit frequently approaches its full load capability, where as the Florida Hotel unit is obviously much less loaded and cycles too frequently. As a result, the compressor of this unit is strained, and the unit's efficiency suffers.

Figure 3: Alabama Nursing Home Unit Nov. '09 Energy Consumption

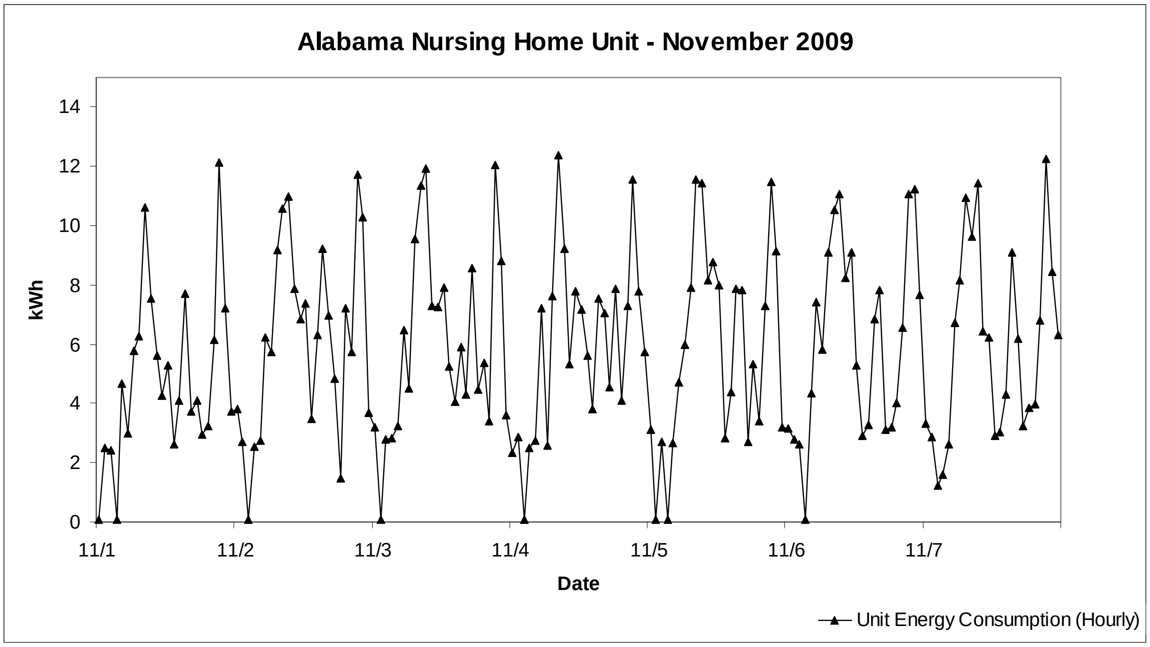


Figure 4. Florida Hotel Unit Nov. '09 Performance

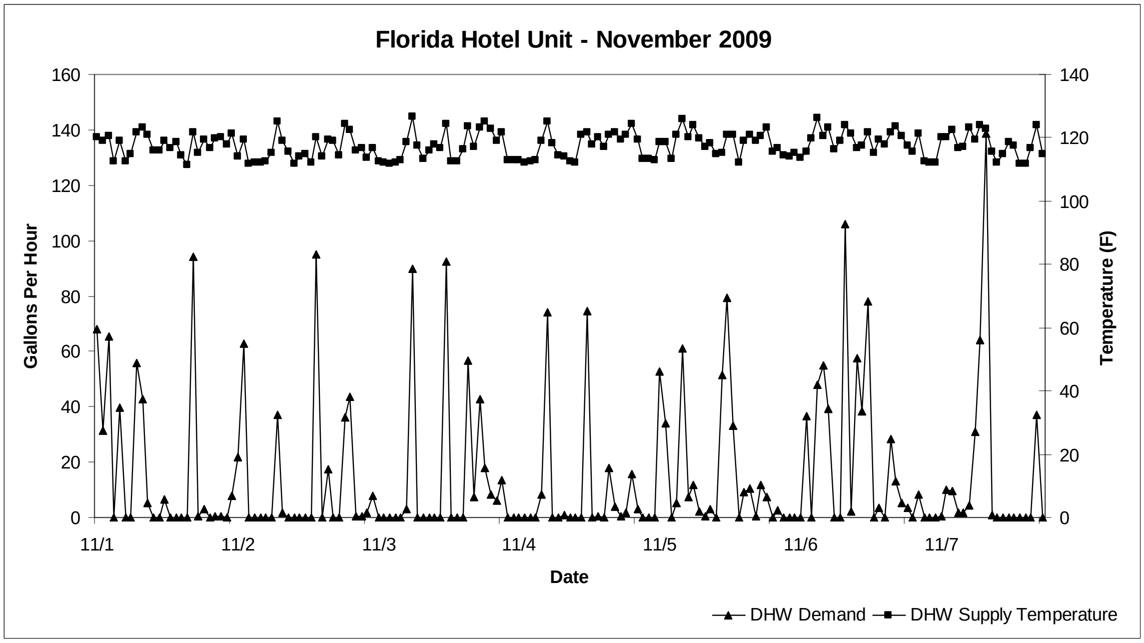
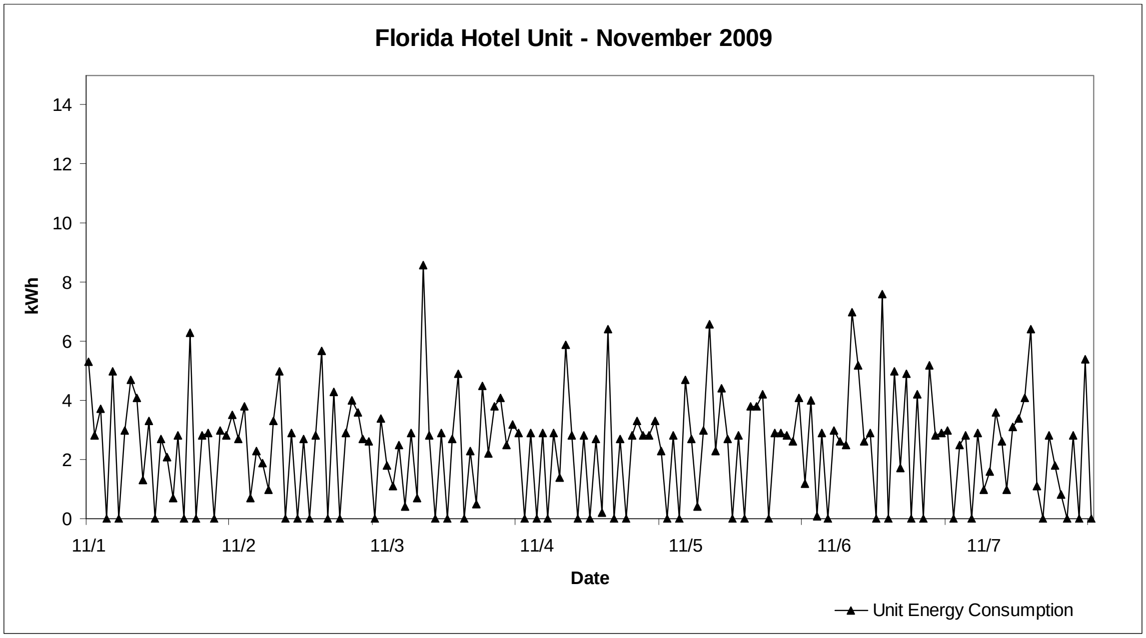


Figure 5. Florida Hotel Unit Nov. ’09 Energy Consumption



The lower capacity Alabama Hotel unit has more trouble keeping up with the DHW demand than the other units as seen in Figure 6. The 300gph and larger draws (which appear to occur only once per day) pull the temperature of the tank down dramatically. However, when the HPWH recovers the tank there is more than enough capacity to satisfy the smaller draws throughout the rest of the day. Furthermore, Figure 7 shows that his unit is well loaded. Though the backup water heating system would be forced to come on during the large draws, the HPWH seems to run a majority of the time to keep the tank satisfied. This unit could potentially provide a greater amount of the building’s DHW needs in warmer weather; the cool weather of November dramatically affects the output of the HWPH and causes the backup heating system to run more than desired.

Summertime operational data for the Alabama Nursing Home unit as seen in Figure 8 shows that the 175,000Btuh HPWH is still able to maintain the storage tank at approximately its 115°F set point as would be expected since the heating output of a HPWH would be higher in the summertime. This unit is more effective at maintaining the tank temperature set point in the summertime as is evident in Figure 9 when compared to Figure 3. The average hourly energy consumption in August is rarely above 7kW, whereas it frequently rose above 11 kW in November; furthermore, the water usage trends were relatively similar in the two months as would be expected in a nursing home.

Figure 6. Alabama Hotel Unit Nov. '09 Performance

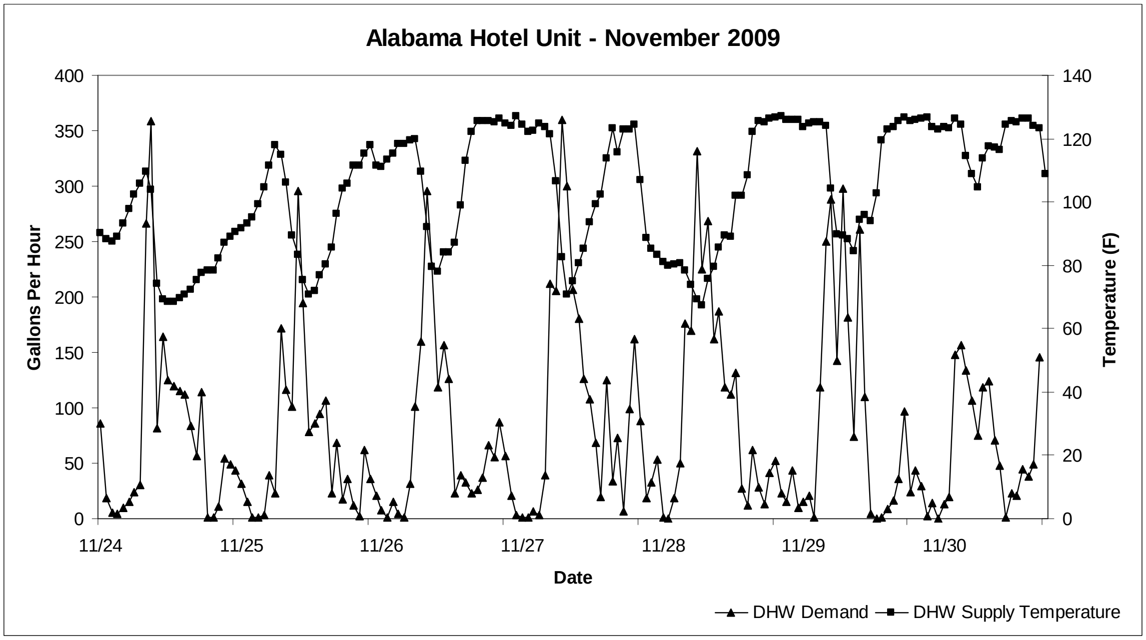
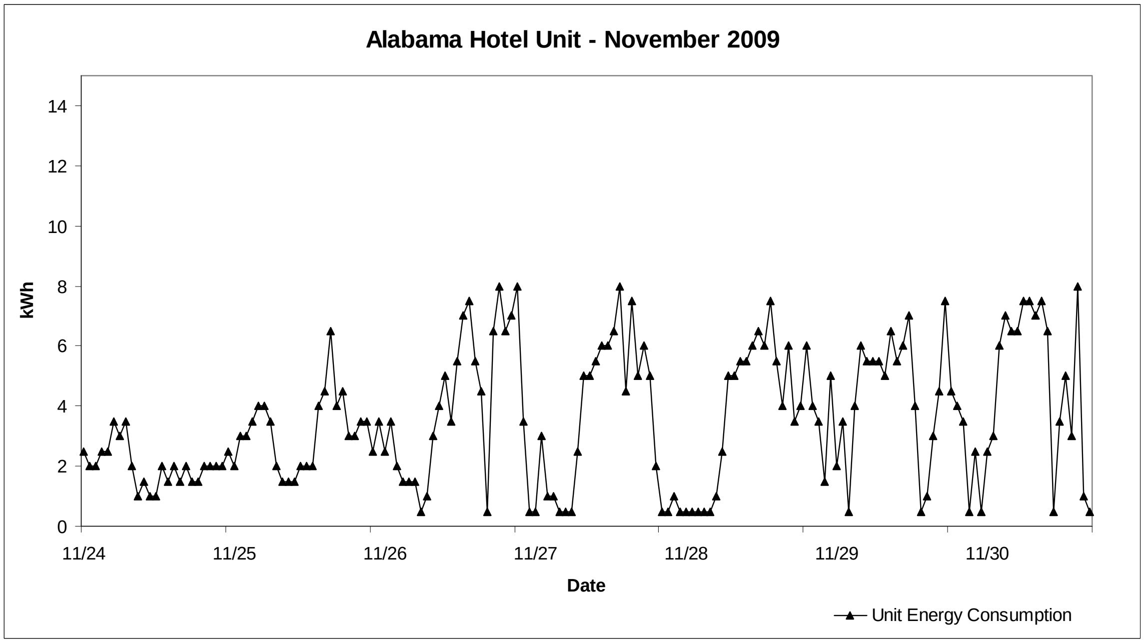


Figure 7. Alabama Hotel Unit Nov. '09 Energy Performance



However, the case of the Florida Hotel is quite different than that of the Alabama Nursing Home. Figure 10 shows that the Florida Hotel unit is able to maintain the storage tank temperature, but when compared to Figure 5 it can be seen that the July water consumption is much higher. In November, the highest hourly water consumption was only around 150 gallons where as in July the hourly water consumption rate frequently rose above 200gph and peaked out at nearly 400gph. Incidentally this is the busiest month for this particular site, so, understandably, the water consumption rate is higher. This higher energy consumption is also seen in Figure 11 as the average hourly energy consumption is much higher than November's data in Figure 5. However, the capacity factor on this particular 175,000Btuh unit is still below a desirable level as will be shown in a forthcoming comparison of the site capacity factors.

Figure 8. Alabama Nursing Home Unit August '09 Performance

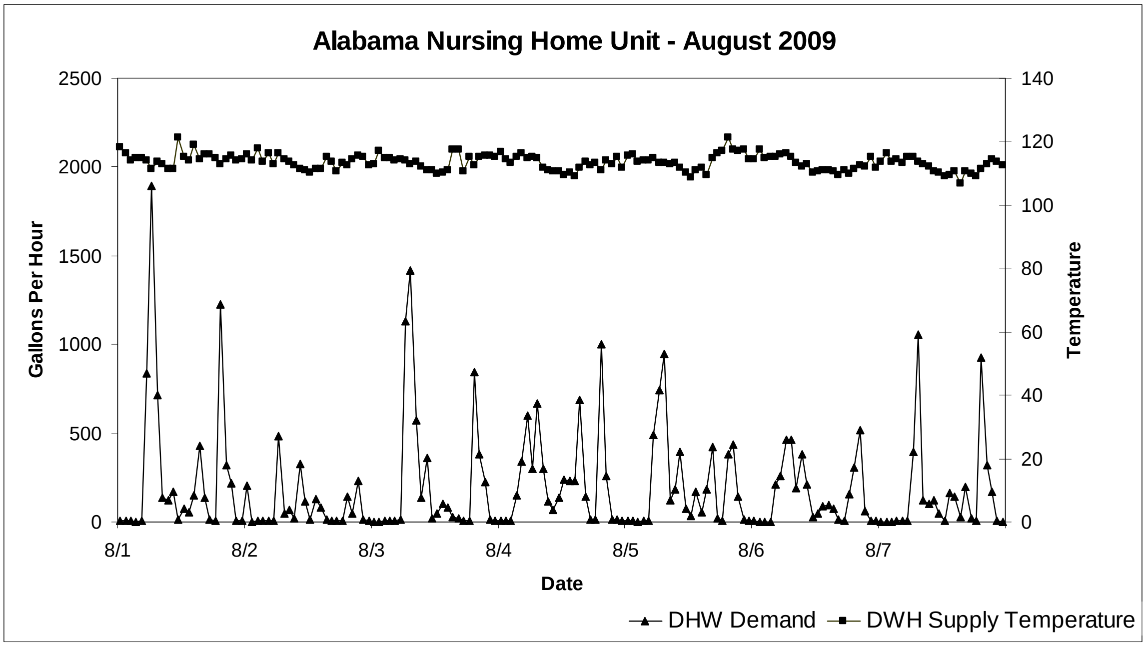


Figure 9. Alabama Nursing Home Unit August '09 Energy Consumption

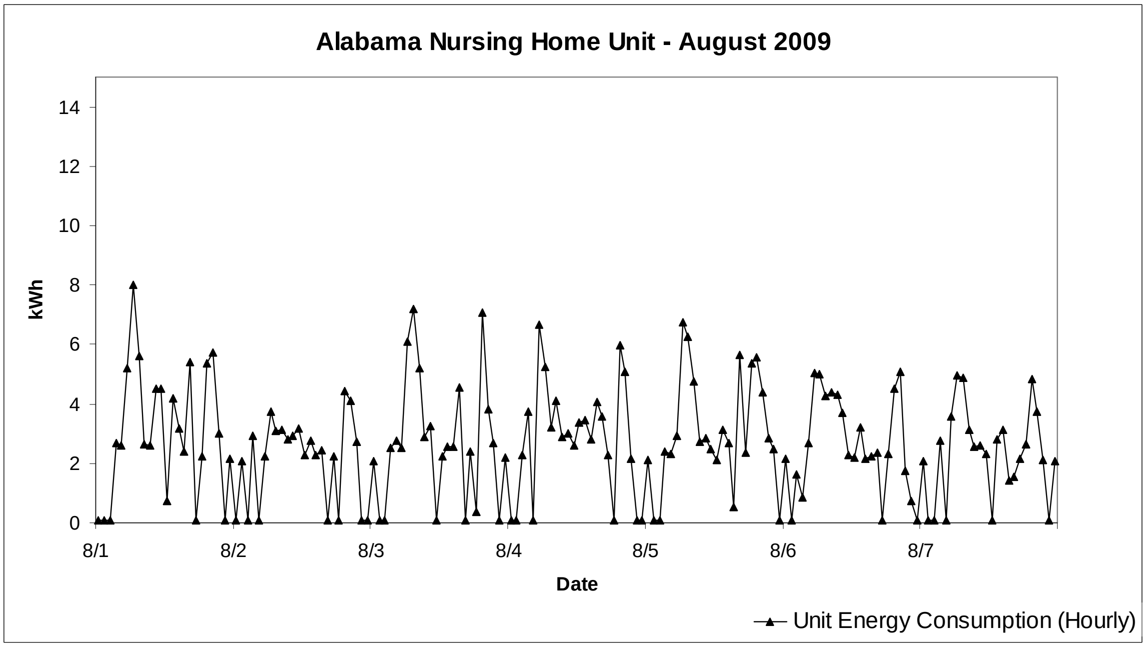


Figure 10. Florida Hotel Unit July ’09 Performance

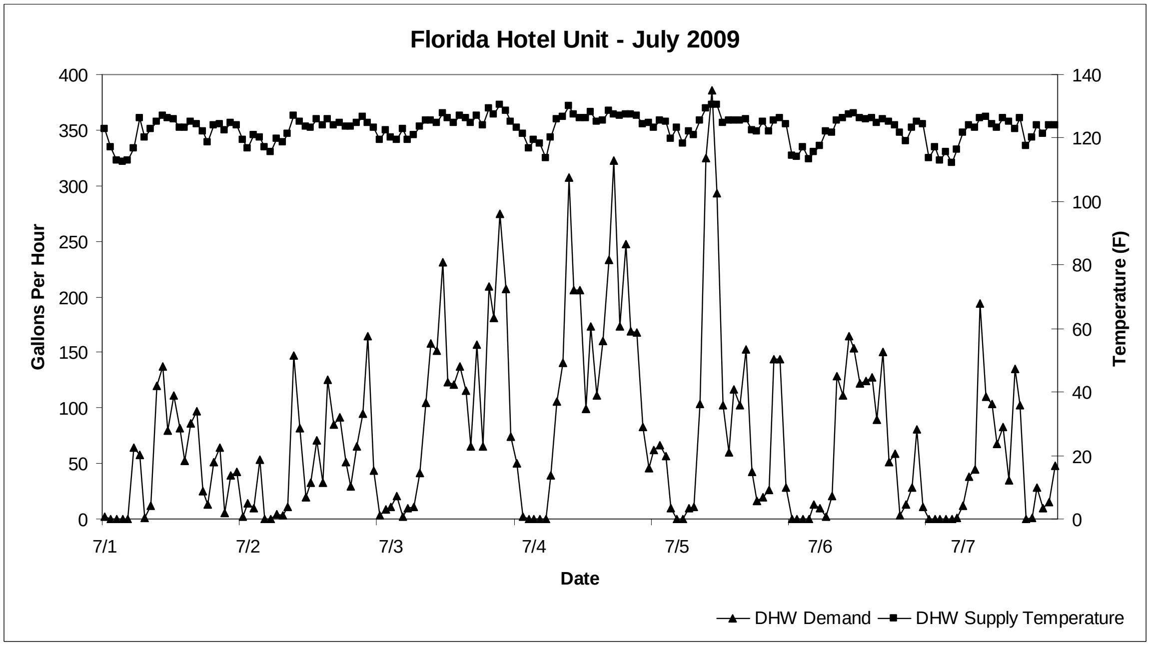
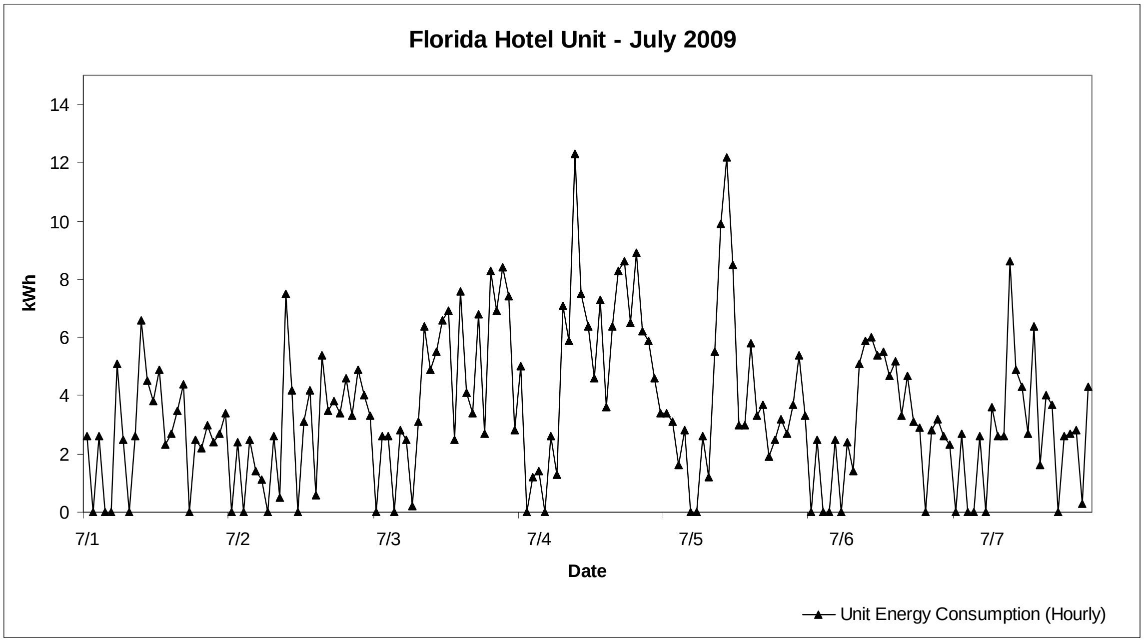


Figure 11. Florida Hotel Unit July ’09 Energy Consumption



A capacity factor was calculated for each of the set of data from each site using a ratio of actual energy usage to maximum possible energy usage as shown in Equation 1.

$$CapacityFactor = \frac{Consumed\_kWh}{Peak\_kW * Hours} \qquad (1)$$

Where Consumed_kWh is the total energy consumption of the HPWH over the analysis period, Peak_kW is the maximum kW draw of the HPWH (as provided by the manufacturer), and Hours is the total number of hours in the analysis period. The calculated capacity factors for each set of presented data are shown in Table 1.

Table 1. Unit Capacity Factors

	Alabama Nursing Home Unit		**Florida Hotel Unit**		**Alabama Hotel Unit**
	Nov-2009	Aug-2009	Nov-2009	Jul-2009	Nov-2009
Total kWh	980	448	410	586	596
Peak kW	12.7	12.7	14	14	8
Total Hours	168	168	168	168	168
Capacity Factor	**0.46**	**0.21**	**0.17**	**0.25**	**0.44**

Furthermore, a coefficient of performance (COP) was calculated for each data set based on the total volume of DHW consumed, the average outlet temperature of the storage tank, and the average inlet temperature of municipal water supply, and the total energy consumed by the HPWH system using Equation 2. The results are presented in Table 2.

$$COP = \frac{WaterVolume * 8.3 * (OutletTemperature - InletTemperature)}{kWh * 3412} \qquad (2)$$

Where 8.3 is a constant conversion factor from gallons to mass based on 100°F water, and 3412 is a constant conversion factor from kWh to Btu.

Table 2: Unit Coefficients of Performance

	Alabama Nursing Home Unit		**Florida Hotel Unit**		**AlabamaHotel Unit**
	Nov-2009	Aug-2009	Nov-2009	Jul-2009	Nov-2009
Unit Energy (kWh)	980	448	410	586	596
Water Volume Consumed (Gallons)	29465	31839	2493	12678	13553
Average Intlet Temperature (°F)	70	88	83	91	65
Average Outlet Temperature (°F)	116	113	118	123	104
COP	**3.36**	**4.32**	**0.52**	**1.70**	**2.16**

Discussion

Taking note of the high COP for most of the data sets, there is obvious potential for energy savings since one Btu of electrical energy yields more than Btu output into the water. Comparable thermal efficiencies for standard gas or electric resistance equipment would range from 70-98% depending on the technology: this means that using conventional equipment only

70-98% of each Btu input would go into the water. Thus, if HPWHs produced an average annual COP of 3 and all commercial buildings DHW systems used a HPWH, then the energy consumption of commercial water heating in the US could drop from 501 trillion Btu per year to less than 167 trillion Btu per year.

This being said, looking at the presented trends can provide insight into the proper application of HPWHs for DHW needs. Though the Alabama Hotel unit does not provide all of the building's DHW needs, it appears to provide a large majority as does the Alabama Nursing Home unit for its building. However, the Florida Hotel Unit appears to be oversized and cycles far too often for efficient operation. This is highlighted by the unit's low COP during summertime operation – which is when the COP should be the greatest – as well as the unit's extremely low COP during fall operation. This low COP is due to the unit's low capacity factor (which is due to the low DHW demand), and the unit's continuously running pump.

The Florida Hotel unit was sized by the installing contractor to meet the building's peak DHW load. It can be seen that this sizing method results in a poor capacity factor for the HPWH, and, as a result, poor efficiency for the system. This particular site has a widely varying DHW load that is seasonally dependant; therefore, the system provides a small water heating load for a majority of the year with a large capacity unit. Even in the peak months of the Florida Hotel site, the unit still does not operate at full capacity. Therefore, similar sites would be well served with two smaller capacity units that would be staged to cycle with the tank temperature. This would allow the system to efficiently meet both the peak and off peak loads. This multiple unit approach is likely the best option for buildings with highly seasonal loads such as buildings in tourist areas.

The Alabama Hotel unit did have some difficulty maintaining the tank temperature set point during the cold weather, but it is expected to provide a large majority of the DHW for its site during the more moderate to warm weather. It can be seen in Table 1 that the capacity factor of the unit is relatively high, however the unit COP (in Table 3) is low when compared to the Alabama nursing home unit. This low COP is believed to be due to a faulty low-ambient cut-off sensor that forced the unit to shut off prematurely. Even though this unit did need a backup heating source to augment the HPWH, its initial investment was considerably less than the 175,000Btuh unit.

A direct comparison between the Alabama Nursing Home unit and the Florida hotel unit highlights the importance of sizing HPWHs for the site in which they are intended. Each of these units is a 175,000 Btu/hr unit, and each site was sized by the same contractor based on the peak water heating load expected to be seen at each site. The capacity factors and resulting COP at each site is substantially different: the Alabama Nursing Home unit runs more than twice as much as the Florida Hotel Unit with an efficiency that is 2-6 time greater.

Each site is relatively unique, and each site requires careful analysis to ensure efficient operation of a HPWH. Careful attention must be paid to the sizing of the storage tank as well as the HPWH itself so the best efficiency is obtained. When a DHW demand profile is available, a simplistic approach to sizing a HPWH is shown in Table 3. Hourly data for the Alabama Nursing home site for a full week is shown for November 2009. For each hour a weekly average is taken, this results in an average DHW demand profile for each hour of the day. Then, a four-hour running average is taken based on the weekly profile; this allows the largest peaks of DHW usage to be smoothed out. A four-hour running average is taken for two reasons: four hours covers large morning and evening periods of hot water usage, and if a steady load is seen by the HPWH for four hours, the unit would be expected to have a good capacity factor. Figure

12 shows the actual average DHW usage profile, the hourly peak profile for the week, and the smoothed four hour running average profile. It is clearly seen how the 4 hour running average takes out the drastic peaks in DHW demand that would result in a grossly oversized HPWH.

Table 3: DHW Demand for Alabama Nursing Home Unit – Nov. '09

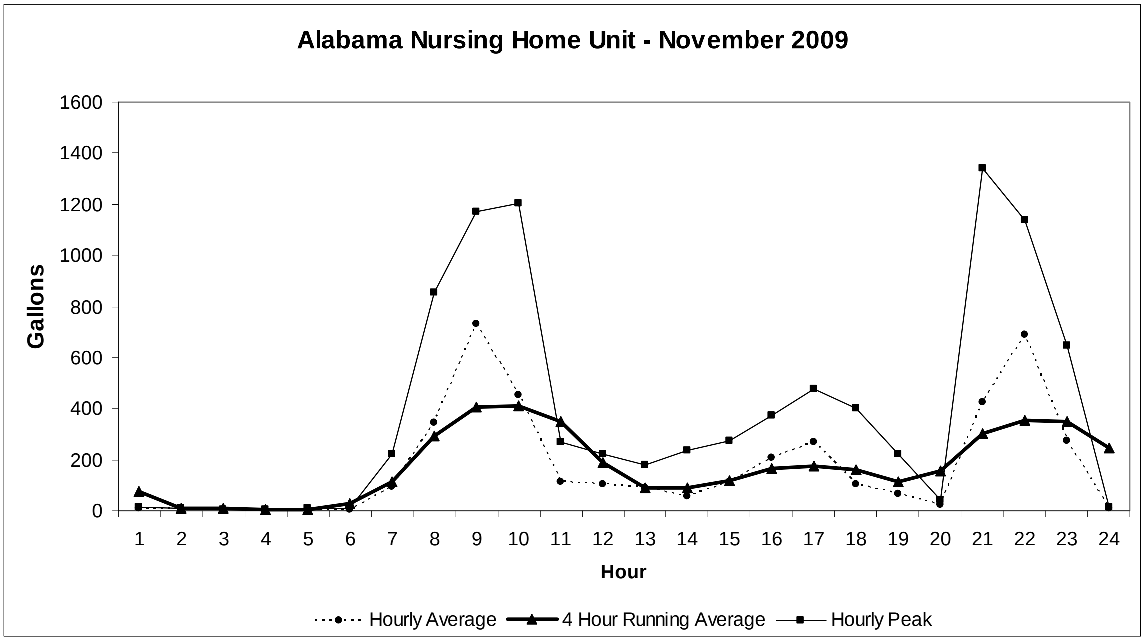
Hour of Day	Sat	Sun	Mon	Tue	Wed	Thu	Fri	Weekly Average for the Hour	4 Hour Running Average
1	10	14	11	9	16	13	11	12	76
2	4	8	7	8	10	10	9	8	7
3	7	6	5	4	6	2	6	5	7
4	6	3	4	4	5	2	5	4	6
5	9	4	5	6	6	5	7	6	5
6	4	5	2	5	4	8	11	5	27
7	10	220	17	11	10	200	186	93	113
8	114	857	349	135	518	163	293	347	295
9	281	868	1170	252	810	663	1095	734	407
10	22	819	118	279	1205	550	196	455	412
11	28	84	268	56	155	26	162	111	351
12	28	223	58	76	110	144	77	102	190
13	26	50	111	162	178	67	41	90	91
14	21	25	238	42	38	33	17	59	91
15	28	272	87	140	38	52	183	114	118
16	134	370	55	373	217	113	201	209	163
17	26	256	170	477	377	400	186	270	174
18	11	88	61	403	21	26	109	103	162
19	15	12	221	138	39	21	14	65	115
20	16	29	29	17	17	12	42	23	154
21	218	438	47	1339	166	563	213	426	300
22	272	557	508	379	1136	1138	820	687	352
23	10	122	521	445	17	647	142	272	349
24	13	9	11	12	10	12	12	11	245
							MAX	734	412
						Storage:	322	gallon	
						HPWH:	412	gallon/hr recovery	

In the lower half of Table 3, the maximum value of the hourly average and the maximum value of the four hour running average are shown to be 734 gallons and 412 gallons, respectively. Therefore, the maximum hourly load seen by the DHW system (storage and HPWH capacity) is 734 gallons in one hour. The highest consistent load seen by the DHW system (four hour running average) is 412 gallons. Therefore, it would make sense that the HPWH should be able to provide 412 gallons of recovery per hour. This is easily converted into a HPWH size when you know the temperature rise of the incoming municipal water to reach set point – which would be dependant on the month being analyzed, so it would be wise to analyze multiple months of data. For example, 412 gallons of capacity in this case with a 50 degree temperature rise – assuming 65°F incoming water and 115°F set point – would result in approximately 171,000Btuh required HPWH capacity. It should be noted that this capacity requirement is at the ambient conditions for the case being analyzed – since the capacity of a HPWH will go down from its nominal rating as the ambient temperature falls. Furthermore, the one hour peak of 734 gallons should be accounted for in storage capacity which, when you subtract out the HPWH recovery capacity, would result in 322 gallons of storage capacity.

Interestingly, the Alabama Nursing Home unit was installed with a 175,000Btuh unit with 350 gallons of storage capacity which is quite close the values obtained in this example. Thus, it is clear why the capacity factor of the Alabama Nursing Home unit is better than the other sites. However, at this point one would want to do an hour by hour analysis to see the capacity factor of the unit and fine tune the storage volume required by the system which is outside the scope of this paper. This is not shown as a definite method to size HPWHs, but it is shown to illustrate the type of analysis that should use when sizing a HPWH for DHW.

The point of this discussion is to emphasize that one should not look at the peak demand of the system as this will result in poor performance for the HPWH. Often the best system performance is achieved when the capacity factor of the HPWH is maximized; some have suggested 70% run time as a good design goal (EPRI 2007). However, when the capacity factor of the unit gets too high, there is a good chance that substantial backup heating will be needed. Therefore, further analysis should be performed to balance the first cost of the system (which is related to HPWH and storage size), the system payback (which is related to unit capacity factor), and the type and cost of supplemental heating.

Figure 12. Smoothed DHW Demand for Alabama Nursing Home Unit



The capacity factor of a system is also highly dependant on the amount of storage capacity available to serve the HWPH. Storage capacity, though limited by the available area in a mechanical room, is a relatively cheap way to increase the capacity factor of a HPWH system. With a larger capacity the buildings DHW system is able to more easily absorb the large peak demands of the building occupants. A larger storage tank also takes longer to drop in temperature; thus, when the HPWH does come on it has a larger volume to heat, and, as a result, will run at a higher capacity for a longer period of time.

Note it was pointed out that storage capacity is a “relatively” cheap way to increase a system’s capacity. Each of these presented sites was required by local code to have an expensive ASME rated tank due to the large storage capacity. These tanks are much more expensive than conventional storage tanks. One should verify if this is required by their local authorities. Furthermore, it is seen as a best practice to insulate these tanks since they will be holding water that is at a higher temperature than the surrounding environment. A considerable efficiency penalty will be seen by the system if the storage tank is not insulated.

Although there is tremendous potential for HPWHs to save energy used for domestic water heating in commercial buildings, there is still a lack of large scale manufacturing and market competition. These studies will be used to show manufacturers the potential of HPWHs for the commercial market and encourage them to introduce commercial products to the market. In the author’s opinion, the best candidates to bring these commercial HPWHs to the market successfully are those with an existing air-conditioning and/or water heating background. This would allow these companies to tap into their existing knowledge and expertise of refrigeration and water heating systems to produce quality, reliable products.

HPWHs would be well suited for commercial buildings with large DHW consumption that occurs relatively evenly over the day: examples include hotels, nursing homes, commercial kitchens, gyms, and hospitals.

The need for more efficient building energy systems is clear, and HPWHs for DHW have a great potential in the commercial market if manufacturers can be encouraged to return the technology to their product offerings.

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