Emerging Technologies

Smart Water Heater Retrofit Controller Lab Study

DR17.06

Prepared by:

Emerging Products
Customer Service
Southern California Edison

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SOUTHERN CALIFORNIA EDISON
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Acknowledgements

Southern California Edison's Emerging Products (EP) group is responsible for this project. It was developed as part of Southern California Edison's Emerging Technologies Program under internal project number DR17.06. Sean Gouw conducted this technology evaluation with overall guidance and management from David Rivers. For more information on this project, contact sean.gouw@sce.com.

EXECUTIVE SUMMARY

Southern California Edison has created an integrated blueprint[1] to help the State of California achieve its greenhouse gas (GHG) emission reduction goals (see Figure 1). This blueprint is referred to as "The Clean Power and Electrification Pathway." Part of what is explored in this pathway, is establishing a goal of up to 30% efficient electrification of commercial and residential space and water heating.

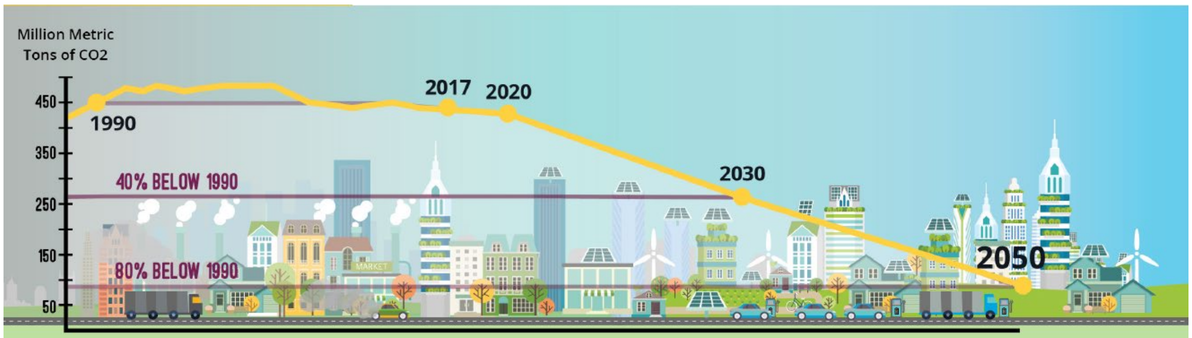

FIGURE 1. MEETING CALIFORNIA'S GHG REDUCTION GOALS (SOURCE: CALIFORNIA AIR RESOURCES BOARD [CARB])[3]

Figure 2 illustrates the "duck curve", published by the California Independent System Operator (CAISO). This curve is a March 31st snapshot of actual and projected data of California's electrical grid net load[7]. This chart shows the challenges of maintaining balance between supply and generation, with the increased adoption of solar generation. The "belly" of the duck shows an overgeneration period, when there is an abundance of solar power. The "neck" of the duck shows the drop-off of solar generation and ramping up of demand.

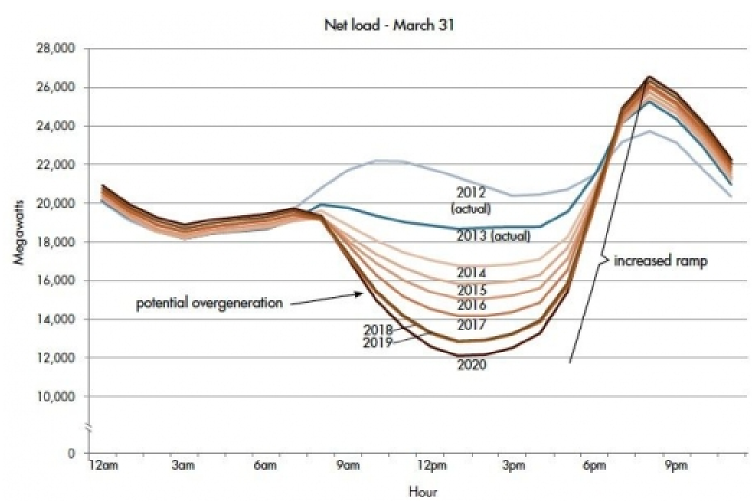

FIGURE 2. THE CAISO DUCK CURVE[2]

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[1] https://www.edison.com/content/dam/eix/documents/our-perspective/g17-pathway-to-2030-white-paper.pdf

[2] https://www.energy.gov/eere/articles/confronting-duck-curve-how-address-over-generation-solar-energy

Water heating is generally regarded as the second largest contributor to energy costs for homes, at approximately 14-18% of utility bills[6]. Water heaters present substantial opportunities for reducing GHG emissions and assisting with grid management. Retrofit controls are available for water heaters, to manage demand/energy consumption and enable Demand Response (DR) control. A retrofit controls product's demand response capabilities are investigated with laboratory testing at SCE's Technology Test Centers.

The tested retrofit controls product is compatible with gas and electric (excluding heat-pump) storage water heaters (not compatible with tankless). The product connects to WiFi, where users interface with it through a cloud-based web portal and/or smart device app. The product indicates hot water availability and tank top temperature, enables manual thermostat scheduling, auto-efficiency settings, usage/energy monitoring, alert settings, and optional connectivity with a heating, ventilation, and air conditioning (HVAC) smart thermostat.

Additionally, a separate internet-browser-based "fleet dashboard" is available for device provisioning and management for utility program purposes, including basic load shifting and curtailment control features. The three main DR control schemes that are of interest to this study are:

- **Load Curtailment Controls:** The water heater responds to temporary DR event signals, to reduce electrical demand by cycling off for the duration of the DR event.
- **Time-of-Use (TOU)-driven controls:** The water heater adjusts its operation (setpoint and operating times) based on the real-time TOU pricing of electricity. Operating times will be shifted to occur during periods of cheaper electricity prices. The water heater controls may take advantage of elevated setpoint temperatures to ensure sufficient thermal capacity for water heating needs.
- **Thermal storage/Grid-Interactive Water Heater (GIWH) controls:** The water heater responds as part of a fleet of aggregated water heaters to shift water heater operating times to influence the electrical end-use load shape (flatten the "duck curve").

Demand response controls for water heaters present great opportunities for GHG reduction and grid management. However, it involves complex interactions that should be well-understood in order to successfully operate demand response programs for water heaters. This laboratory study offers detailed insight into the complex interactions that can take place in a water heater. A continuous balance must be maintained between meeting hot water needs, mitigating safety concerns for scalding and pathogen development, and managing energy use. This investigation confirmed that this technology shows promise to enable utility programs to implement the three main DR strategies identified, with some given nuances that can be addressed.

- **Load Curtailment:** Load curtailment may be scheduled through the internet-based fleet dashboard as single load curtailment events or recurring load shift events. Single load curtailment events can force the water heater to shut off heating or modify temperature setpoint of the retrofit controller. Recurring load shift events did not offer the selection between setpoint and heating shut-off. The fleet dashboard is suitable for use by program implementers, but it is likely that communication of load curtailment events for high volumes of products is preferred through interaction with utility demand response automation servers via openADR. Utilities should work with controls manufacturers to ensure an appropriate communication pathway is established.

- **TOU Controls:** At the time of this project, all SCE TOU rates could be configured into the TOU controls of the retrofit controls product, but only through the user portal. There did not appear to be any other telemetry/monitoring to confirm the TOU schedule that was selected. Utilities should work with controls manufacturers to ensure an appropriate communication pathway is established for setting and verification of appropriate TOU controls.
- **GIWH:** This is not a selectable mode in either the user portal or the fleet dashboard. It was approximated using available fleet dashboard/user portal means. At the time of this project, it was approximated with load curtailment from the fleet dashboard, in conjunction with temperature boost scheduling configured in the user portal. It is unclear what utility grid condition telemetry would best feed into the product in order to inform real-time GIWH operation and how those signals will be communicated. Utilities should work with controls manufacturers to ensure an appropriate communication pathway is established and controls schemes are informed with the appropriate telemetry.

The research questions first posed at the outset of this study are answered as follows:

1. What are the demand savings benefits of the identified DR control schemes?

   Water heaters come in a variety of sizes and types for residential applications. The baseline water heater established in this study had two 4.5 kW heating elements that are never on at the same time. Total peak demand of the water heater was therefore 4.5 kW. This peak can be curtailed or shifted with the retrofit controls product with the DR schemes identified. However, under even baseline operation, the timing of heating events will vary based on hot water usage and the inherent inconsistencies in the water heater's mechanical controls. Additionally, heating element runtimes are fairly short occurrences throughout the 24-hour test period. Total heating runtimes under baseline operation were 56 minutes per day for the weekday profile Test 1a and 104 minutes per day for the weekend profile Test 2a.

2. What happens to water heater thermal performance for the identified DR control schemes?

   a. What are the average/maximum/minimum water temperatures in the water heater tank under typical usage, with and without, the retrofit controls?

Test #		Description	WH Whole Tank Daily Avg Med	Daily Max	Daily Min
1	a	Base-weekday	121.9	125.1	75.7
	b	Base-weekday-repeat	122.9	125.4	75.9
	c	Base-weekday-repeat	122.0	125.9	75.6
3	-	Base, Ret Ctrl On	122.3	124.9	75.4
4	a	Load Curtailment-weekday	122.4	125.5	74.9
	b	Load Curtailment-weekday-repeat	122.6	125.5	75.5
5	a	TOU-DA-weekday	122.4	126.5	75.2
	b	TOU-DA-weekday-repeat	122.0	124.5	75.0
2	a	Base-weekend	120.3	123.6	72.7
	b	Base-weekend-repeat	120.2	124.1	72.3
	c	Base-weekend-repeat	120.3	124.2	72.4
6	a	TOU-DA-weekend	119.0	124.0	70.4
	b	TOU-DA-weekend-repeat	118.6	124.6	70.6
7	a	GIWH-weekend	117.5	124.1	69.7
	b	GIWH-weekend-repeat	116.0	122.9	69.9

b. Under the DR control schemes, do the retrofit controls maintain water temperatures suitable to continue meeting the needs of typical home water usage?

The retrofit controls appear to be capable of delivering hot water temperatures per hot water draw event, similar to those of baseline operation. The mild deviations of water heater outlet temperatures per hot water draw event were within the typical deviations observed during baseline repeat testing. Mild deviations were more frequent under the approximated GIWH controls, likely attributed to the mechanical thermostat limitations of the temperature boost feature, which are easily remedied. The retrofit controller generally makes determinations for maintaining a minimal amount of available hot water, regardless of the selected control scheme.

c. Do the reduced water temperatures appreciably increase the risk of pathogen growth, such as legionella bacteria?

The retrofit controls and associated DR schemes of operation do not appear to significantly increase risk of pathogen growth. The critical area appears to continue to be at the bottom of the water tank, where biofilms were originally understood to proliferate within this style of water heater. It is important to advocate for mitigation of these risks through best practices/manufacturer recommendations for water heater maintenance/flushing. The retrofit controls contain temperature boosting features that may be able to assist with controlling pathogen growth. Further studies on appropriate strategies should be considered.

d. Do any of the DR control schemes involve elevated water temperatures to increase/optimize energy storage or appreciably increase the risk of scalding?

The GIWH approximation (boost mode) did involve raising water heater setpoint. However, the effective setpoint was limited by the physical settings of the mechanical thermostat during testing. This can be easily addressed in practice. The water heater is certainly capable of producing scalding water temperatures both with and without the retrofit controller. These risks should be mitigated through use of mixing valves regardless of the presence of the retrofit controller, as required by plumbing code and informed by best design practices.

3. In terms of customer experience and interaction, what can be expected with the retrofit technology under each of the DR control schemes? Questions may include but are not limited to:

    a. Is Automated Demand Response (ADR) available/enabled for this retrofit technology? Explain.

    At the time of the project, this technology was not enabled to communicate through openADR. Demand response communication is handled using the internet-based fleet dashboard. Additional work is required to facilitate communication between this product and utility demand response automation servers.

    b. Is the interface easy to use? What are the customer options for overriding? Other noteworthy features?

    At the time of this project, the version of the user portal seemed clean and intuitive. TOU scheduling may appear confusing and tedious for consumers; therefore it is important that utilities mitigate the burden of adopting TOU controls as much as possible. Pre-loaded TOU rate schedules should be readily available and updated on an ongoing basis. For DR program implementers, monitoring/setting of TOU rates schedules can be available to ensure correct rates schedules are used. TOU controls can be easily enabled/disabled in the user portal.

    For load curtailment and load shift functions initiated from the fleet dashboard, the user portal indicates events once they are in progress. There did not appear to be any user override options or advanced notification of scheduled load curtailment/load shift events.

    Other noteworthy features not explored in this study are the hot water usage learning function, the three efficiency settings, the display of the water heater as a thermal battery with % capacity indication, and the historical tracking of energy & hot water usage.

Further studies should be pursued to establish more understanding of characterizing broader market offerings for retrofit controls and onboard controls. Classifications of product families should be established and pursued for DR program development. DR program requirements/specifications related to communications and DR scheme capabilities should be established.

Any demand response programs associated with water heaters should advocate industry-accepted best practices for ensuring safe operation, emphasizing mitigation of risks associated with scalding and pathogen growth. Best practices for maintenance should be emphasized. Opportunities for temperature-boost controls, leveraged as pathogen growth mitigation strategies should be explored.

Further studies should be pursued to establish an acceptable tool for predicting hot water usage, for water heater DR program use. Resources for T-24 energy modeling purposes, and the tool established for the DOE Building America program should be considered.

The challenges in addressing energy-conscious best practices for water heater sizing, and plumbing system design seem somewhat analogous to the HVAC industry. Water heater measures should always be conscious of the water heater and connected plumbing at the system level (just as optimal HVAC measures for RTUs should consider the entire attached duct system). The industry-accepted best practices/design do not appear to be as detailed and well-established as those in the HVAC industry (e.g., ACCA manuals, ASHRAE Handbooks, etc.). DR water heater programs should promote research and advocacy for standardizing energy-conscious best practices for water heater design and adopt those procedures as part of water heater DR program implementation.

ABBREVIATIONS AND ACRONYMS

ADR	Automated Demand Response
CAISO	California Independent System Operator
CCEL	Calorimeter Controlled Environment Laboratory
DR	Demand Response
EIA	U.S. Energy Information Administration
GHG	Greenhouse gas
GIWH	Grid-Interactive Water Heater
GPM	Gallons Per Minute
HVAC	Heating, Ventilation, and Air Conditioning
LDB	Legionnaire's Disease Bacteria
RC	Retrofit Controller
RTD	Resistance Temperature Detector
TMY3	Typical Meteorological Year Data
TOU	Time of Use
TTC	SCE's Technology Test Centers

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EQUATIONS

INTRODUCTION

Southern California Edison has created an integrated blueprint[3] to help the State of California achieve its greenhouse gas (GHG) emission reduction goals (see Figure 3). This blueprint is referred to as "The Clean Power and Electrification Pathway." Part of what is explored in this pathway, is establishing a goal of up to 30% efficient electrification of commercial and residential space and water heating.

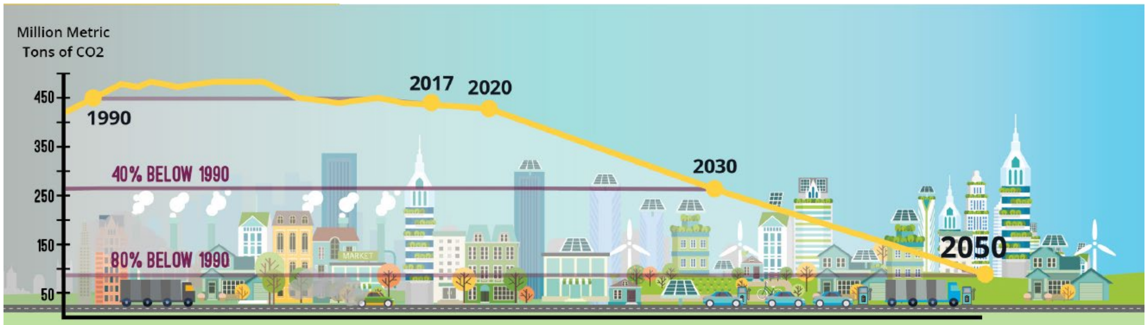

FIGURE 3 . MEETING CALIFORNIA'S GHG REDUCTION GOALS (SOURCE: CALIFORNIA AIR RESOURCES BOARD [CARB])[3]

WATER HEATERS

Figure 4 illustrates the various possible configurations and fuel types of water heaters. Water heating is generally regarded as being the second largest contributor to energy costs for homes, at approximately 14-18% of utility bills[6]. The U.S. Energy Information Administration (EIA) provides support with analyzing the typical water heater characteristics of the California market. In 2009, out of 12.2 million housing units[4]:

- 11% use electricity as the water heater fuel source, and 84% are natural gas (remaining use propane/liquefied petroleum gas, fuel oil, other, or do not use hot water).
- 2% use tankless water heaters, 98% use storage tank water heaters.
    - Age of all water heaters: 16% are less than 2 years old, 16% are 2-4 years old, 30% are 5-9 years old, 18% are 10-14 years old, 7% are 15-19 years old, and 14% are 20+ years old. (Typical water heater useful life is roughly 10 years[5])
- Tank size of water heaters
    - Where the main water heater serves one housing unit,
        - 9% are small-sized (30 gal or less).
        - 46% are medium-sized tank water heaters (31-49 gal).

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[3] https://www.edison.com/content/dam/eix/documents/our-perspective/g17-pathway-to-2030-white-paper.pdf

[4] https://www.eia.gov/consumption/residential/data/2009/

[5] https://www.nachi.org/lifespan-water-heater.htm, https://www.lowes.com/projects/repair-and-maintain/when-to-replace-a-water-heater/project

    - 25% are large-sized tank water heaters (50+ gal).
- Where the main water heater serves two or more housing units
    - 2% are medium-sized tank water heaters (31-49 gal).
    - 14% are large-sized tank water heaters (50+ gal).
- 2% are tankless where size is minimal/not applicable.

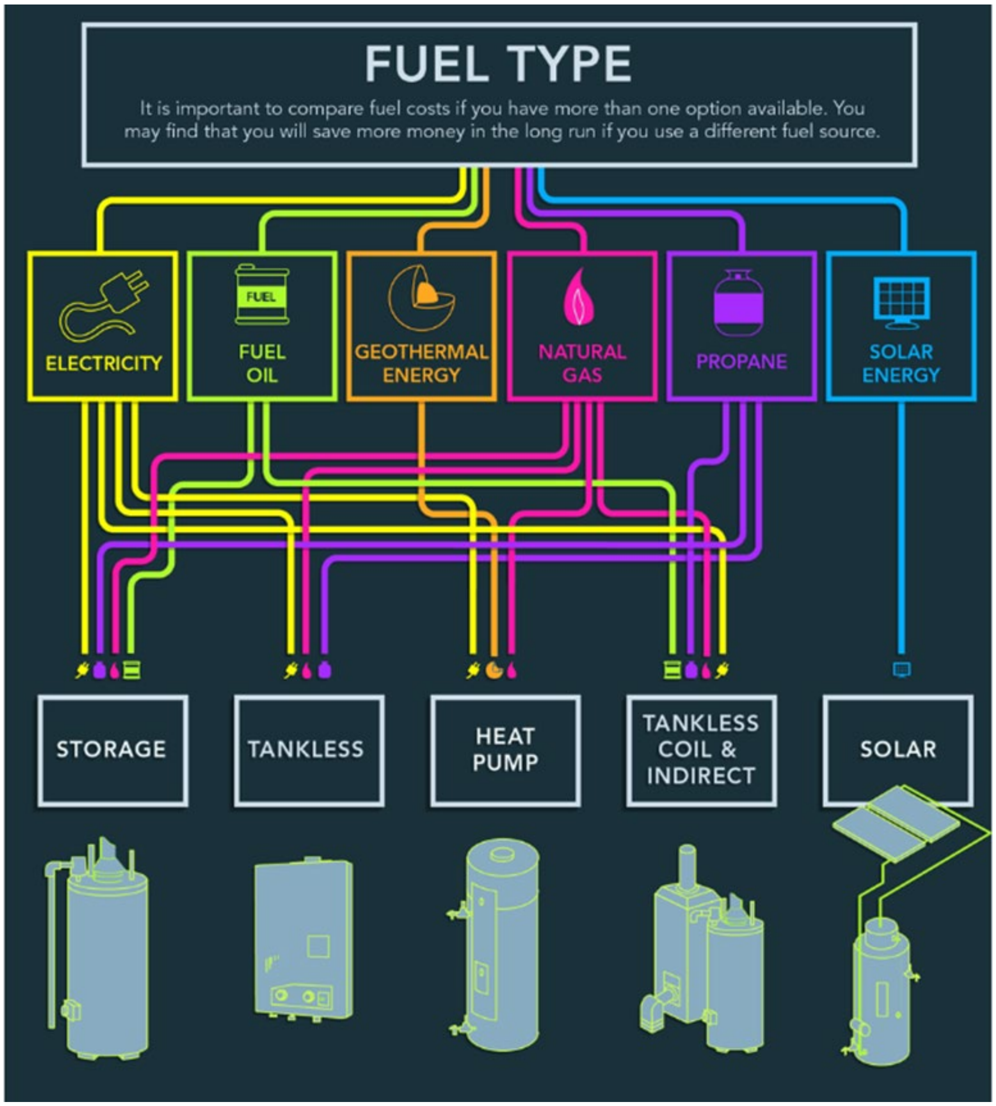

FIGURE 4. WATER HEATER FUEL TYPES & CONFIGURATIONS[6]

[6] https://energy.gov/articles/new-infographic-and-projects-keep-your-energy-bills-out-hot-water

THE DUCK CURVE

Figure 5 illustrates the “duck curve”, published by the California Independent System Operator (CAISO). This curve is a March 31st snapshot of actual and projected data of California’s electrical grid net load[7]. This chart shows the challenges of maintaining balance between supply and generation, with the increased adoption of solar generation. The “belly” of the duck shows an overgeneration period, when there is an abundance of solar power. The “neck” of the duck shows the decrease of solar generation, and increase of demand.

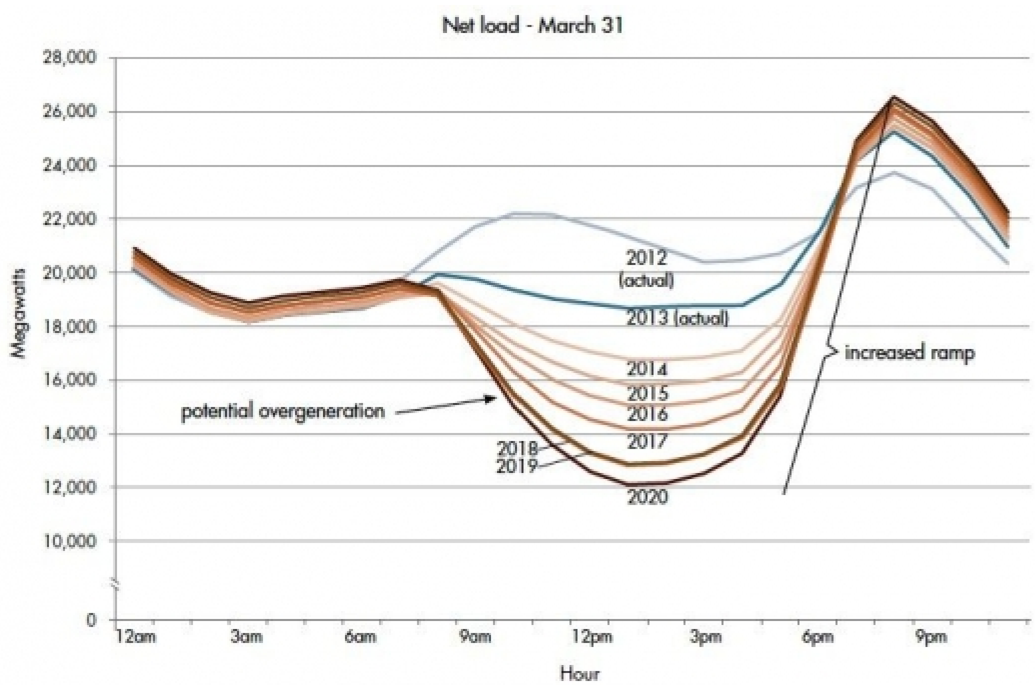

FIGURE 5. THE CAISO DUCK CURVE[7]

[7] https://www.energy.gov/eere/articles/confronting-duck-curve-how-address-over-generation-solar-energy

SCE Residential Demand Response Programs and Time of Use Rates

At the time of this project, two demand response programs were offered by SCE for residential customers: the Summer Discount Plan and Smart Energy programs.

- Summer Discount Plan[8,9]
  - "When you participate in the Summer Discount Plan, you save by voluntarily allowing us to shut down your A/C for up to 6 hours a day during "energy events" we may call during periods of high electricity demand, or emergencies. We supply and install a device on your home or central-A/C unit to remotely shut it off during energy events."
  - "You can choose your level of participation from 4 options: Save more with our "standard" option, or choose the flexibility of our "override" option, which lets you opt out of up to 5 energy event days a year. Then decide between Maximum Savings (100% cycling) or Maximum Comfort (50% cycling.)"
- Smart Energy Program (formerly known as Save Power Days; Save Power Day Incentive Plus or PTR-ET-DLC)[10,11]
  - "During an SCE Energy Event, we will notify your smart thermostat service provider to adjust the temperature setting on your thermostat to limit A/C usage. Events can be called anytime throughout the year between 11 a.m. and 8 p.m. for a minimum of one hour and up to four hours, per day, on non-holiday weekdays. Multiple events per day can be called but cannot exceed a maximum of four hours per day."
  - "Earn up to $40 in bill credits‡ yearly for participating from June 1 to October 1, plus get additional savings during energy events."
  - "You can choose to adjust the thermostat temperature at your discretion, but your savings may be impacted."

At the time of this project, SCE offered both Tiered and Time-of-Use (TOU) electrical rate plans. The following TOU plans were available[12]:

- **TOU-D-A:** This option is better for low and medium energy users (less than 700 kWh/month). TOU-D-A features higher peak rates that are offset by a monthly baseline credit.
  - Highest rates: Weekdays 2:00 -8:00 PM
  - Daily Basic Charge: $.03 per day

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[8] Accessed 7/6/2018. https://www.sce.com/wps/portal/home/residential/rebates-savings/summer-discount-plan

[9] Accessed 7/6/2018. Link to Terms & Conditions

[10] Accessed 7/6/2018. https://pages.email.sce.com/SCESmartBonus/

[11] Accessed 7/6/2018. Link to Terms & Conditions

[12] Accessed 3/1/2018 here

- Minimum Daily Charge: $.34
- Baseline Credit: $.08 per kWh up to your monthly baseline allocation (For example, if a customer's monthly allocation is 200 kWh, a $16 credit will be reflected on the monthly bill.
- Summer: June to September (Four months)

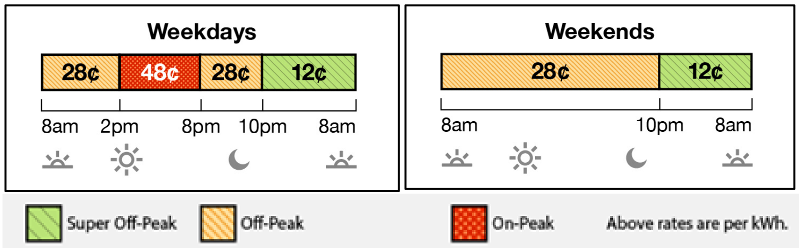


FIGURE 6. TOU-D-A PEAK PERIODS – SUMMER, JUNE TO SEPTEMBER (FOUR MONTHS)

- Winter: October to May (Eight months)

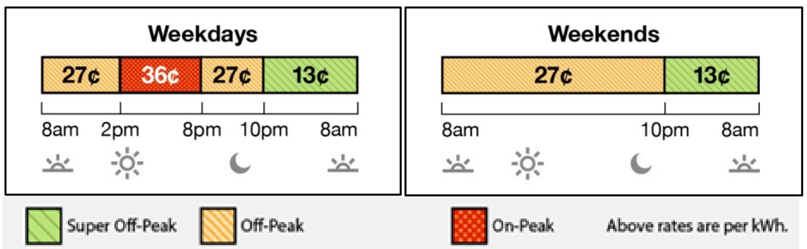


FIGURE 7. TOU-D-A PEAK PERIODS – WINTER, OCTOBER TO MAY (EIGHT MONTHS)

- **<u>TOU-D-B</u>:** This option is better for high energy users (more than 700 kWh/month). TOU-D-B features lower peak rates, but a higher daily basic charge and no baseline credit.
  - Highest rates: Weekdays 2:00 -8:00 PM
  - Daily Basic Charge: $.55 per day
  - Minimum Daily Charge: None
  - Baseline Credit: None
  - Summer: June to September (Four months)

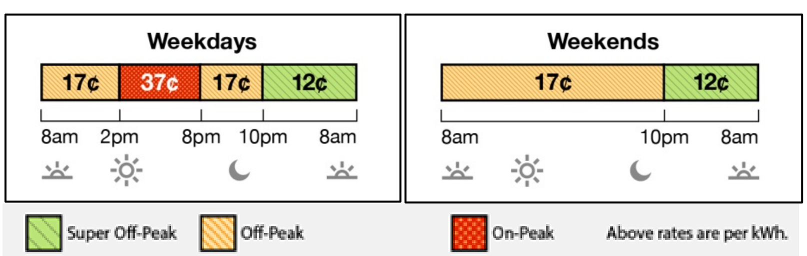


FIGURE 8. TOU-D-B PEAK PERIODS – SUMMER, JUNE TO SEPTEMBER (FOUR MONTHS)

- Winter: October to May (Eight months)

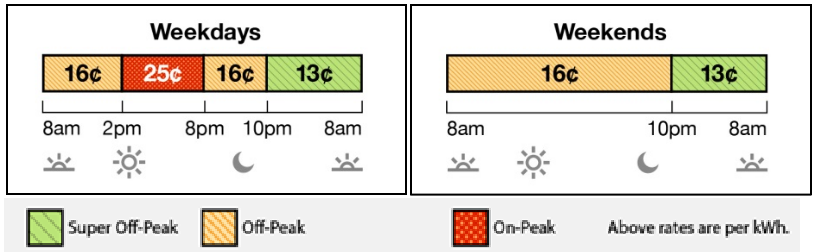


FIGURE 9. TOU-D-B PEAK PERIODS – WINTER, OCTOBER TO MAY (EIGHT MONTHS)

- **TOU-D-T:** Combines Time-Of-Use and Tiered Rate Plan pricing
  - Highest rates: Weekdays 12:00 -6:00 PM
  - Daily Basic Charge: $.03 per day
  - Minimum Daily Charge: $.33
  - Baseline Credit: None
  - TOU-D-T features two tiers of pricing determined by your baseline allocation.
    - Tier 1: Up to 130% of baseline allocation
    - Tier 2: More than 130% of baseline allocation
  - Summer: June to September (Four months)

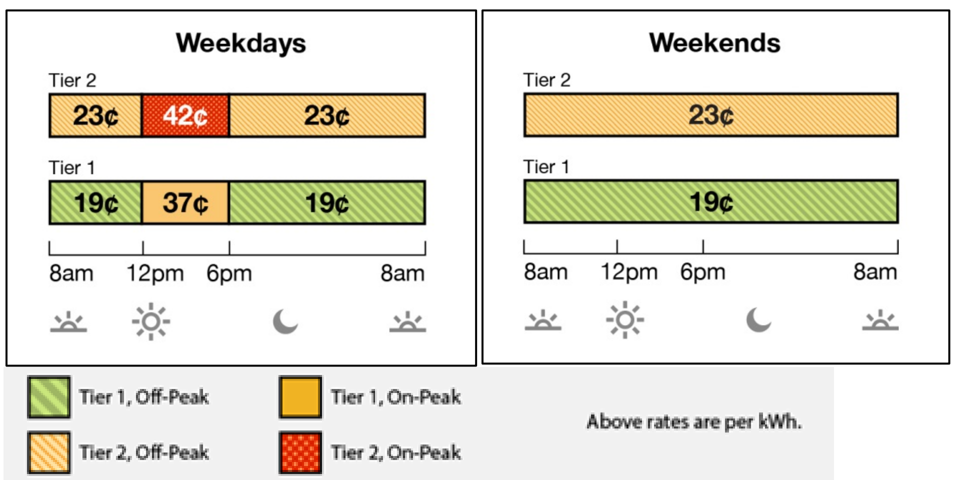


FIGURE 10. TOU-D-T PEAK PERIODS – SUMMER, JUNE TO SEPTEMBER (FOUR MONTHS)

- Winter: October to May (Eight months)

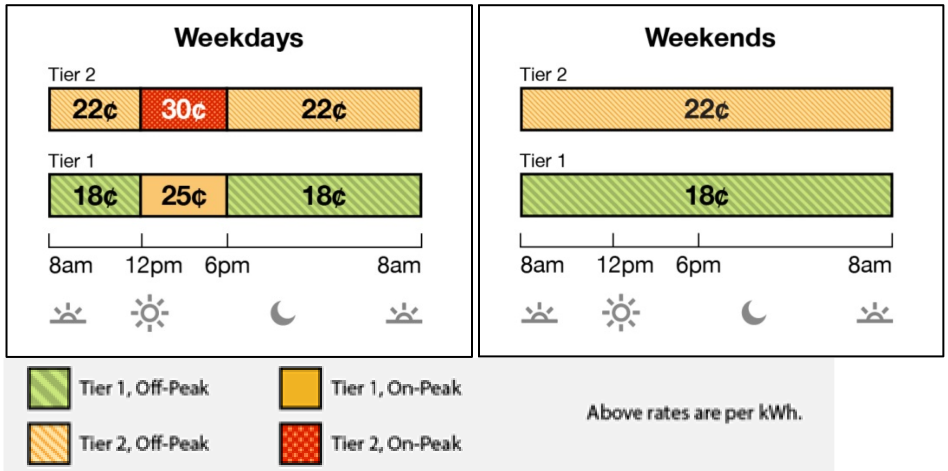


FIGURE 11. TOU-D-T PEAK PERIODS – WINTER, OCTOBER TO MAY (EIGHT MONTHS)

- **TOU-EV-1**: Rate for electric vehicle charging stations with a dedicated meter.
  - Highest rates: Every day 12:00 -9:00 PM
  - Monthly Meter Charge: $2.76
  - Baseline Credit: None
  - Summer: June to September (Four months)

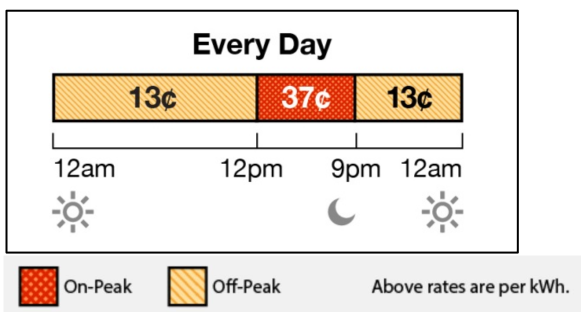


FIGURE 12. TOU-EV-1 PEAK PERIODS – SUMMER, JUNE TO SEPTEMBER (FOUR MONTHS)

  - Winter: October to May (Eight months)

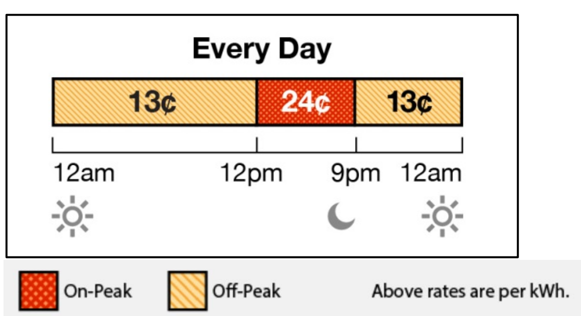


FIGURE 13. TOU-EV-1 PEAK PERIODS – WINTER, OCTOBER TO MAY (EIGHT MONTHS)

- **<u>TOU- D-4-9PM</u>:** Better for customers who stay up late at night. May benefit smaller households in coastal areas with moderately sized homes or condos.
  - Highest rates: Summer Weekdays 4:00 -9:00 PM
  - Daily Basic Charge: .03¢ per day
  - Minimum Daily Charge: 34¢ per day

    Baseline Credit: .08¢ per kWh up to your monthly baseline allocation (For example, if a customer's monthly allocation is 200 kWh, a $16 credit will be reflected on the monthly bill. This option is eligible for bill protection.
  - Summer: June to September (Four months)

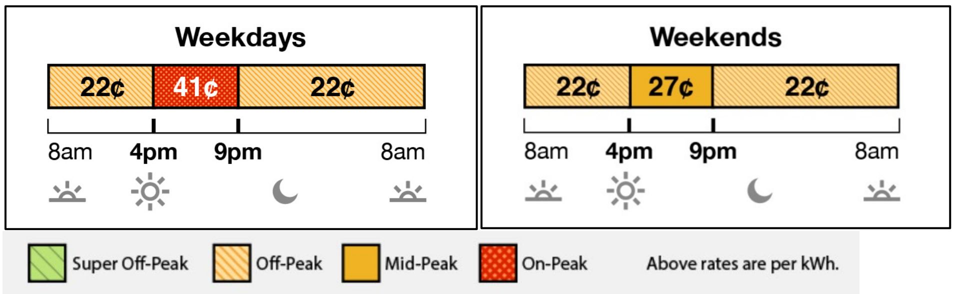


FIGURE 14. TOU-D-4-9PM PEAK PERIODS – SUMMER, JUNE TO SEPTEMBER (FOUR MONTHS)

  - Winter: October to May (Eight months)

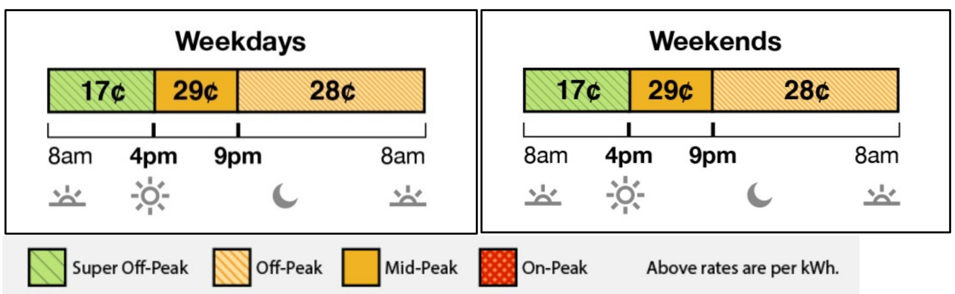


FIGURE 15. TOU-D-4-9PM PEAK PERIODS – WINTER, OCTOBER TO MAY (EIGHT MONTHS)

- **<u>TOU- D-5-8PM</u>:** This option is better for customers who end the night early. It may benefit customers who are home during the day and tend to live in smaller rented dwellings.
  - Highest rates: Summer Weekdays 5:00 -8:00 PM
  - Daily Basic Charge: .03¢ per day
  - Minimum Daily Charge: 34¢ per day
  - Baseline Credit: .08¢ per kWh up to the monthly baseline allocation (For example, if a customer's monthly allocation is 200 kWh, a $16 credit on your bill will be reflected on the monthly bill. This option is eligible for bill protection.

- Summer: June to September (4 months)

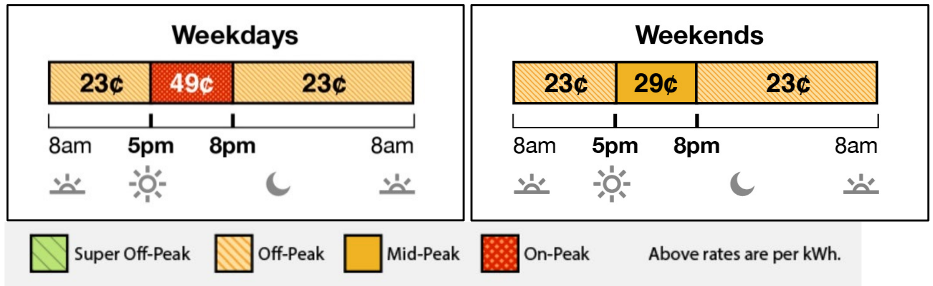


FIGURE 16. TOU-D-5-8PM PEAK PERIODS – SUMMER, JUNE TO SEPTEMBER (FOUR MONTHS)

- Winter: October to May (8 months)

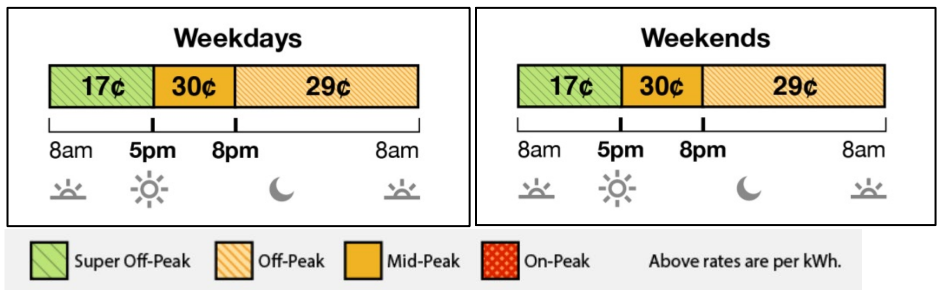


FIGURE 17. TOU-D-5-8PM PEAK PERIODS – WINTER, OCTOBER TO MAY (EIGHT MONTHS)

HOT WATER SAFETY

When considering appropriate hot water temperatures, a proper balance must be struck between meeting hot water needs, optimizing energy efficiency, and mitigating safety concerns. For the purposes of this project, two safety concerns highlighted are scalding water temperatures and Legionnaire's Disease Bacteria (LDB) growth.

Maintaining elevated temperatures helps prevent proliferation of bacteria in the tank, but also increases energy use and scalding temperature risk. Maintaining lower temperatures reduces energy use and scalding temperature risk, but increases the risk for proliferation of pathogens in the water heater tank. Storage tank temperature stratification must also be considered. Parameters such as tank size, heating source placement, and development of scaling within the water heater over time can drive temperature stratification. Table 1 shows the hot water temperature ranges for scalding temperature times, and Legionnaire's Disease response[13].

TABLE 1. HOT WATER TEMPERATURE RANGES FOR SCALDING TEMPERATURE AND LEGIONNAIRE'S DISEASE RESPONSE[13]

WATER TEMP (F)	LEGIONELLAE NOTES		LENGTH OF CONTACT FOR A MILD DEGREE BURN	LENGTH OF CONTACT FOR A SECOND DEGREE BURN	OTHER NOTES
176	Disinfection Range				
158					
154			Instantaneous	1 Second	
151	Die within 2 minutes				
149			1 Second	2 Seconds	
140	Die within 32 minutes		2 Seconds	5 Seconds	
131	Die within 5 to 6 hours		5 Seconds	25 Seconds	
126			30 Seconds	90 Seconds	
122	Growth Range	Can survive, but do not multiply	1 Minute	5 Minutes	
120			3 Minutes	9 Minutes	
116			35 Minutes	45 Minutes	Pain Threshold Approximate
115	Ideal Growth Range				
110					Normal Hot Shower
95					

[13] American Society of Sanitary Engineering, "Understanding Potential Water Heater Scald Hazards" White Paper. http://www.asse-plumbing.org/WaterHeaterScaldHazards.pdf

Water Temp (F)	Legionellae Notes		Length of Contact for a Mild Degree Burn	Length of Contact for a Second Degree Burn	Other Notes
68	Growth Range	Survive but dormant			Cold water in storage tanks, piping, decorative fountains, and other equipment should ideally be kept below 68°F.

Technology/Product Evaluation & Background

Water Heater Test Unit

Figure 18 shows the electric water heater test unit used for this laboratory assessment project. Water heater key specifications are as follows[14]:

- Make/Model: Rheem XE40M06ST45U1
- Electric fuel type
- Medium Profile, Indoor, Storage
- Rated/nominal tank capacity = 40 gal/36 gal (claim ample hot water for 2-4-person household)
- 240 Volt, 18.75 Amp
- Two 4,500 watt heating elements
- Energy Factor/Uniform Energy Factor = 0.95/0.93
- First Hour Delivery = 51 gallons/hr.
- Weight = 106 lbs.
- Depth/height/width = 20.25 in/48.5 in/20.25 in
- Tank valve size/water connection size = 0.75 in/0.75 in
- Max/min temperature 150°F/90°F

[14] https://www.homedepot.com/p/Rheem-Performance-40-Gal-Medium-6-Year-4500-4500-Watt-Elements-Electric-Tank-Water-Heater-XE40M06ST45U1/205810725

FIGURE 18. WATER HEATER TEST UNIT

Figure 19 shows common general components in a typical electric tank water heater.

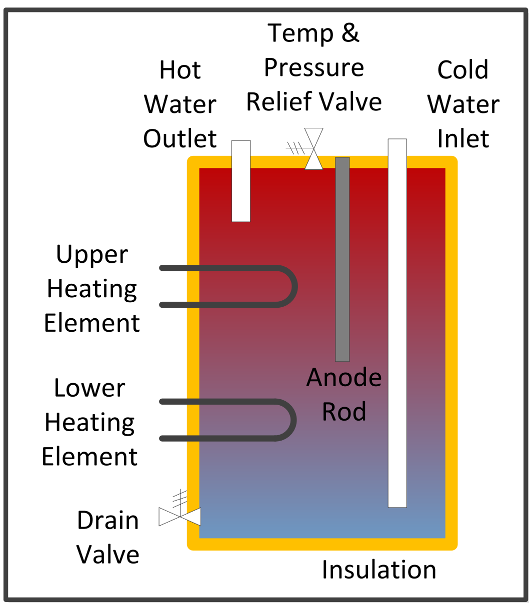


FIGURE 19. ELECTRIC STORAGE WATER HEATER GENERAL DIAGRAM

Generally, the controls sequence of an electric resistance water heater with two heating elements is understood as a dual-zone temperature control system (upper/lower zones), where the heating elements are not allowed to operate simultaneously. The understanding of the controls sequence is illustrated with the following example scenario of a large hot water draw event. (See Figure 20.):

1. A hot water event occurs, which depletes hot water in the lower zone of the tank and displaces it with cold water. The lower heating element turns on in response.
2. The hot water event continues which depletes hot water in the upper zone of the tank and displaces it with cold water. The lower heating element turns off and the upper heating element turns on in response.
3. The hot water event finishes. The upper heating element heats the upper zone of water to a sufficient temperature. The upper heating element then turns off, and the lower heating element turns on.
4. The lower element has brought the lower zone to a sufficient temperature, and turns off. The entire tank is at a sufficient temperature.

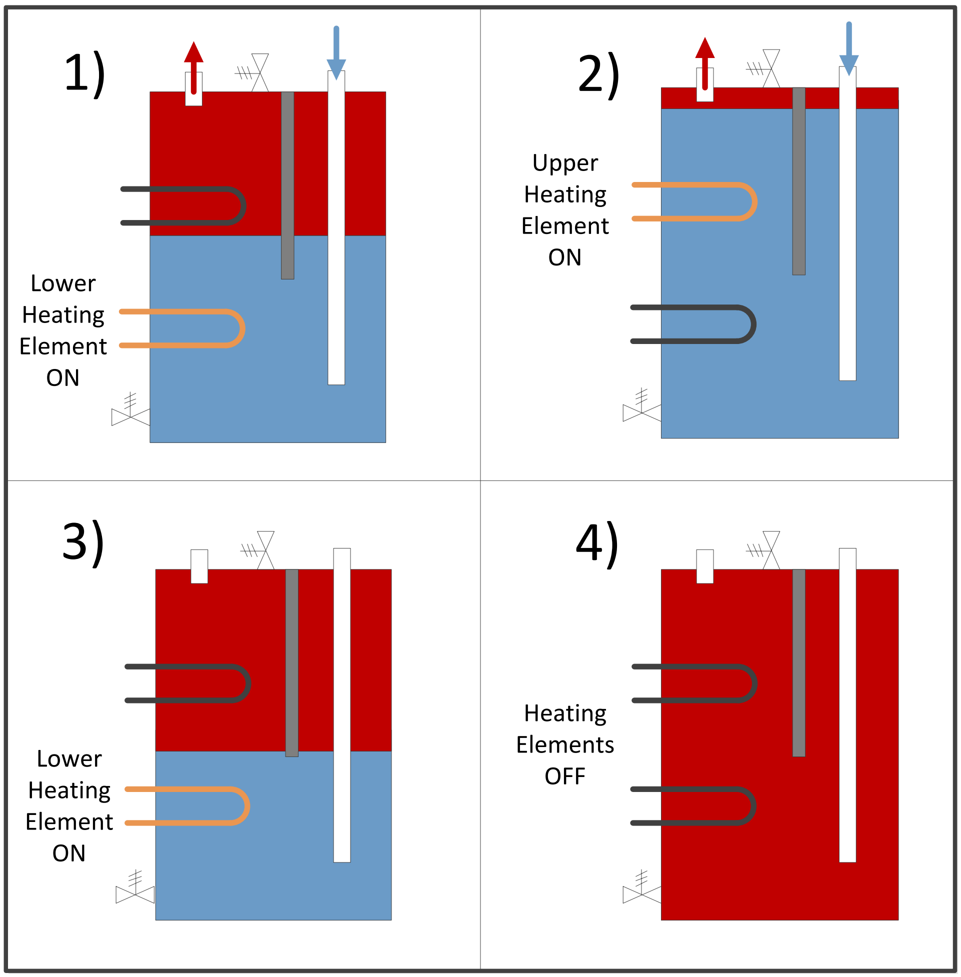


FIGURE 20. ELECTRIC STORAGE WATER HEATER GENERAL HEATING ELEMENT SEQUENCE

WATER HEATER RETROFIT CONTROLS TEST UNIT

Retrofit controls are available for water heaters, to reduce demand/energy consumption and enable Demand Response (DR) control. The product investigated in this project enables three main DR control schemes:

- **Load Curtailment Controls:** The water heater responds to temporary DR event signals to reduce electrical demand by cycling off for the duration of the DR event.
- **TOU-driven controls:** The water heater adjusts its operation (setpoint and operating times) based on the real-time TOU pricing of electricity. Operating times will be shifted to occur during periods of less expensive electricity prices. The water heater controls may take advantage of elevated setpoint temperatures to ensure sufficient thermal capacity for water heating needs.
- **Thermal storage/Grid-Interactive Water Heater (GIWH) controls:** The water heater responds as part of a fleet of aggregated water heaters to shift water heater operating times to influence the electrical end-use load shape (flatten the "duck curve").

Details and specifications of the DR retrofit controller (RC) are understood include:

- Compatibility with gas and electric (excluding heat-pump) storage water heaters. (Not compatible with tankless water heaters.)
- Connects to WiFi, cloud-based web portal and smart device app interface and the following features are available:
  - Hot water availability, manual scheduling, auto-efficiency settings, usage/energy monitoring, alert settings, tank top temperature
  - TOU-driven controls can be enabled.
  - Connectivity with HVAC Nest Learning Thermostat
- Fitting for tank sensor, connects to ¾ in temperature and pressure relief valve.
- Internet-browser-based "fleet" dashboard for device provisioning and management, including basic load shifting and curtailment control features
- Measurement & Verification available for fleet users through AWS S3 data "pipeline"
- Autonomously cuts power to the water heater and issues an alert if the tank temperature crosses a high threshold (75°C/167°F) that potentially indicates a dangerous thermostat failure.
- Electrical Input:
  - Electric Water Heater: 208/240 VAC, 50/60 Hz
  - Gas Water Heater: 120 VAC, 50/60 Hz
- Power Consumption: 5W

Figure 21 through Figure 28 show various screenshots from the user portal and fleet dashboard interfaces.

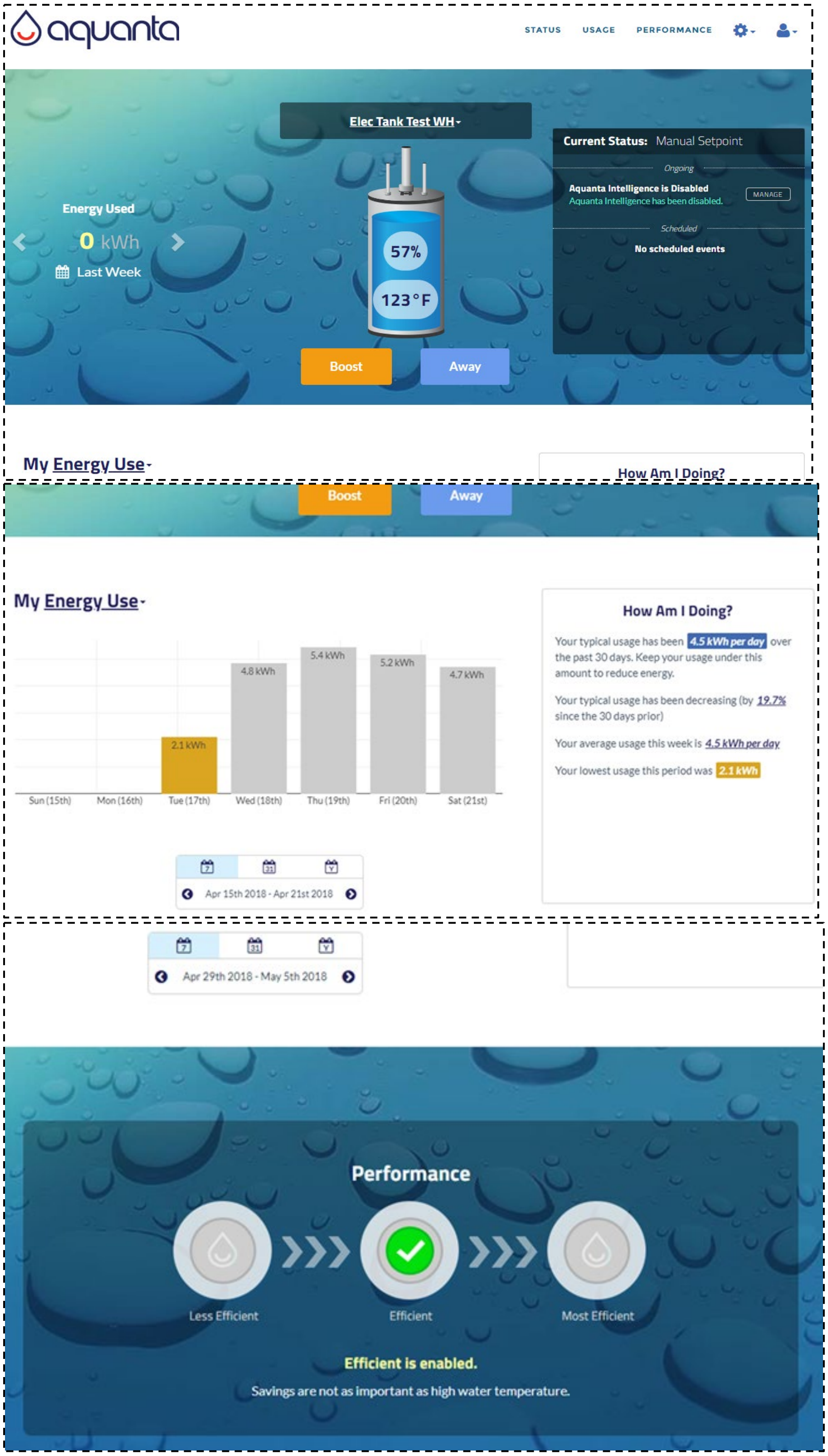


FIGURE 21. USER PORTAL SCREENSHOTS – PT. 1

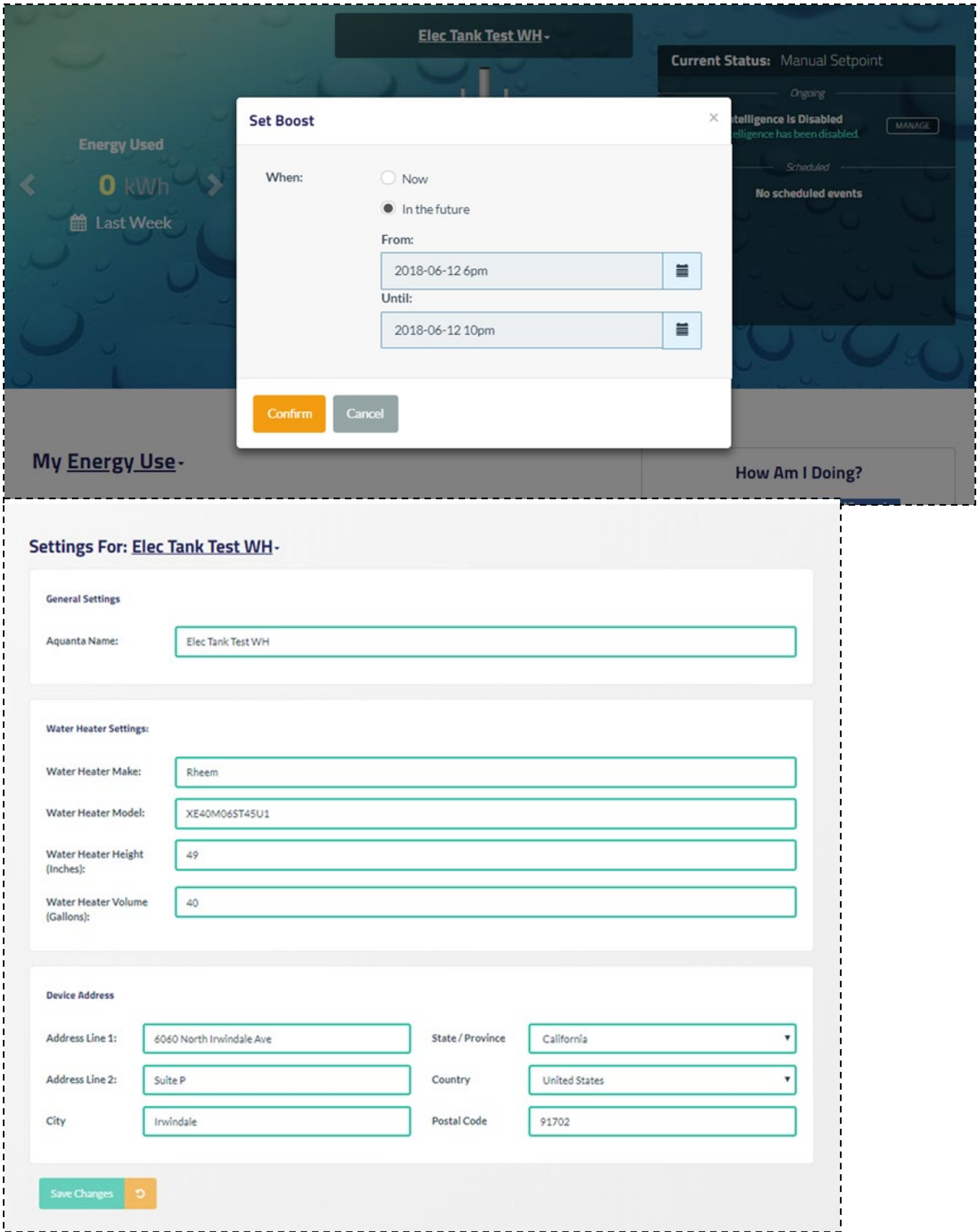
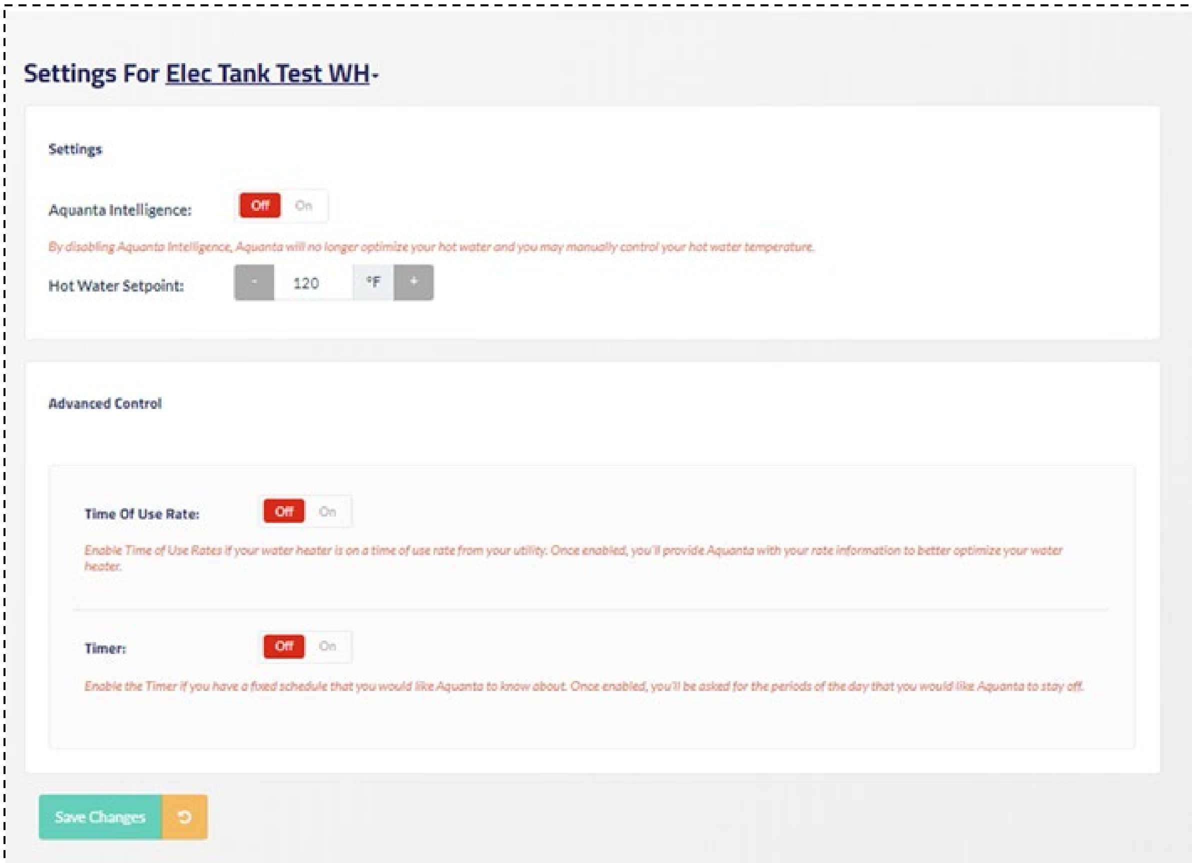


FIGURE 22. USER PORTAL SCREENSHOTS – PT. 2



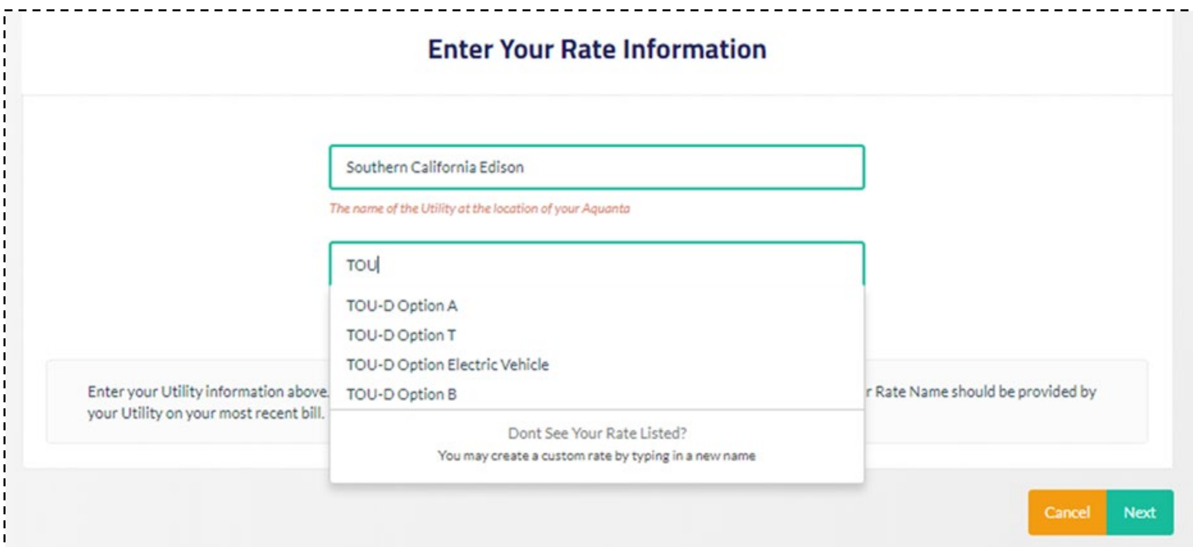


FIGURE 23. USER PORTAL SCREENSHOTS – PT. 3

FIGURE 24. USER PORTAL SCREENSHOTS – PT. 4

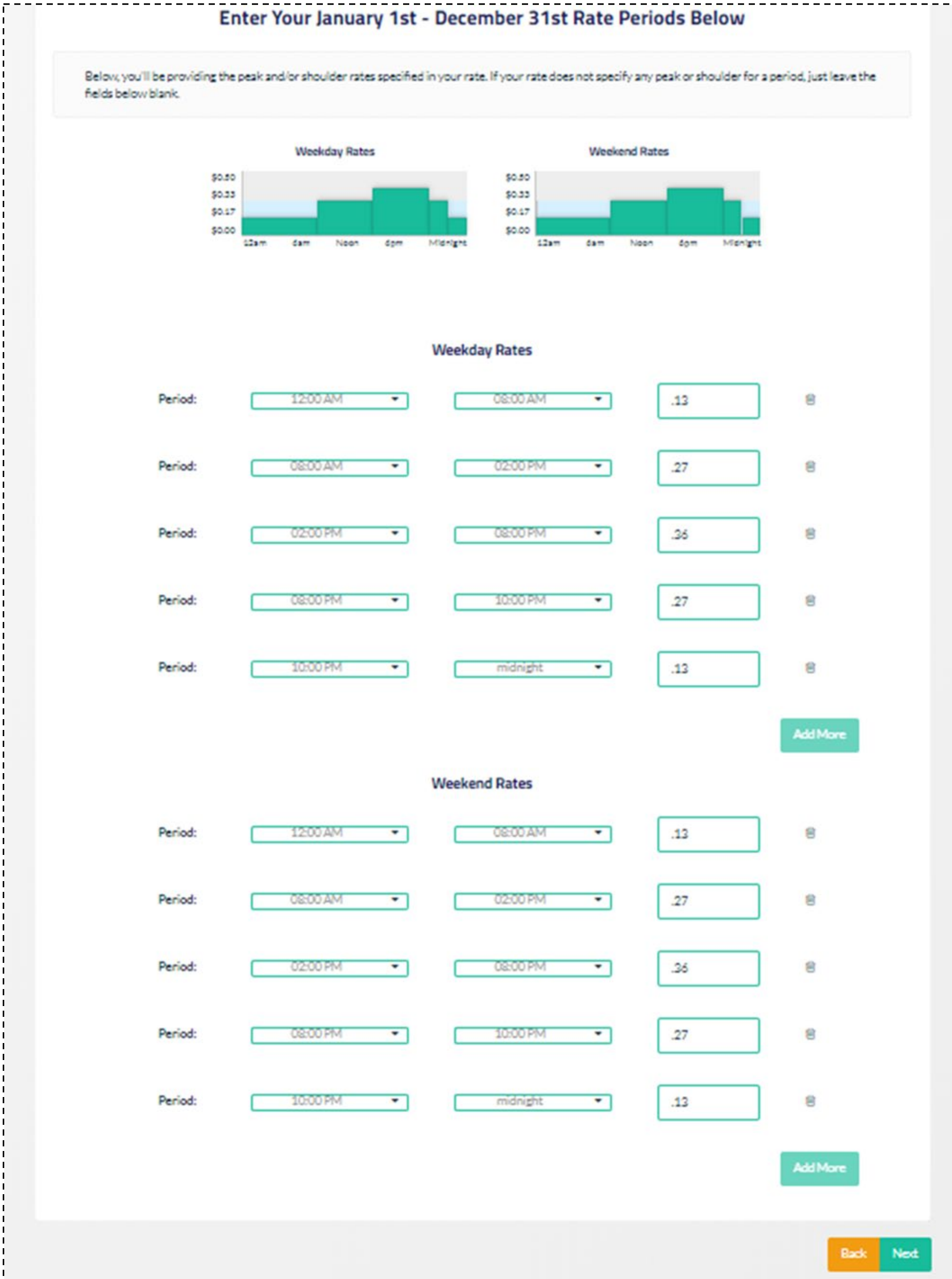


FIGURE 25. USER PORTAL SCREENSHOTS – PT. 5

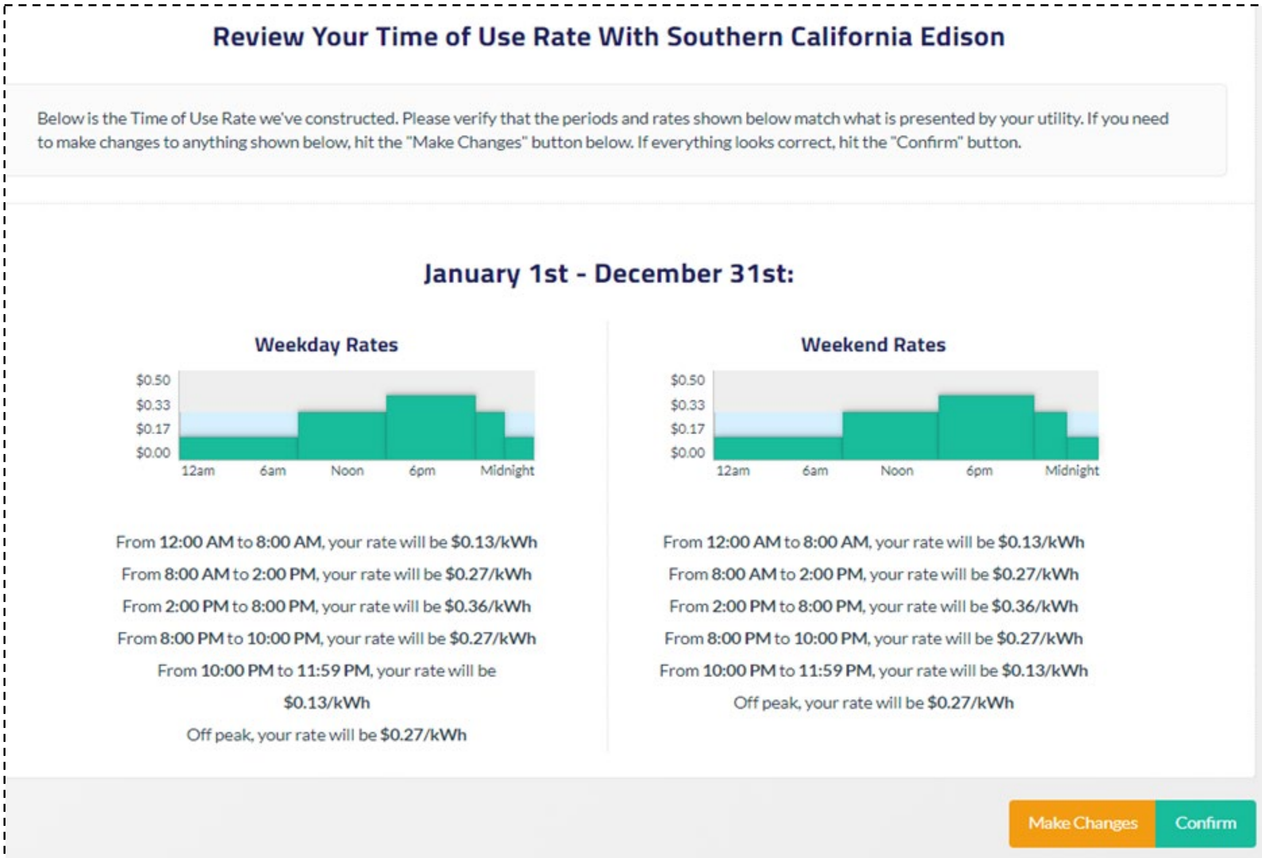


FIGURE 26. USER PORTAL SCREENSHOTS – PT. 6

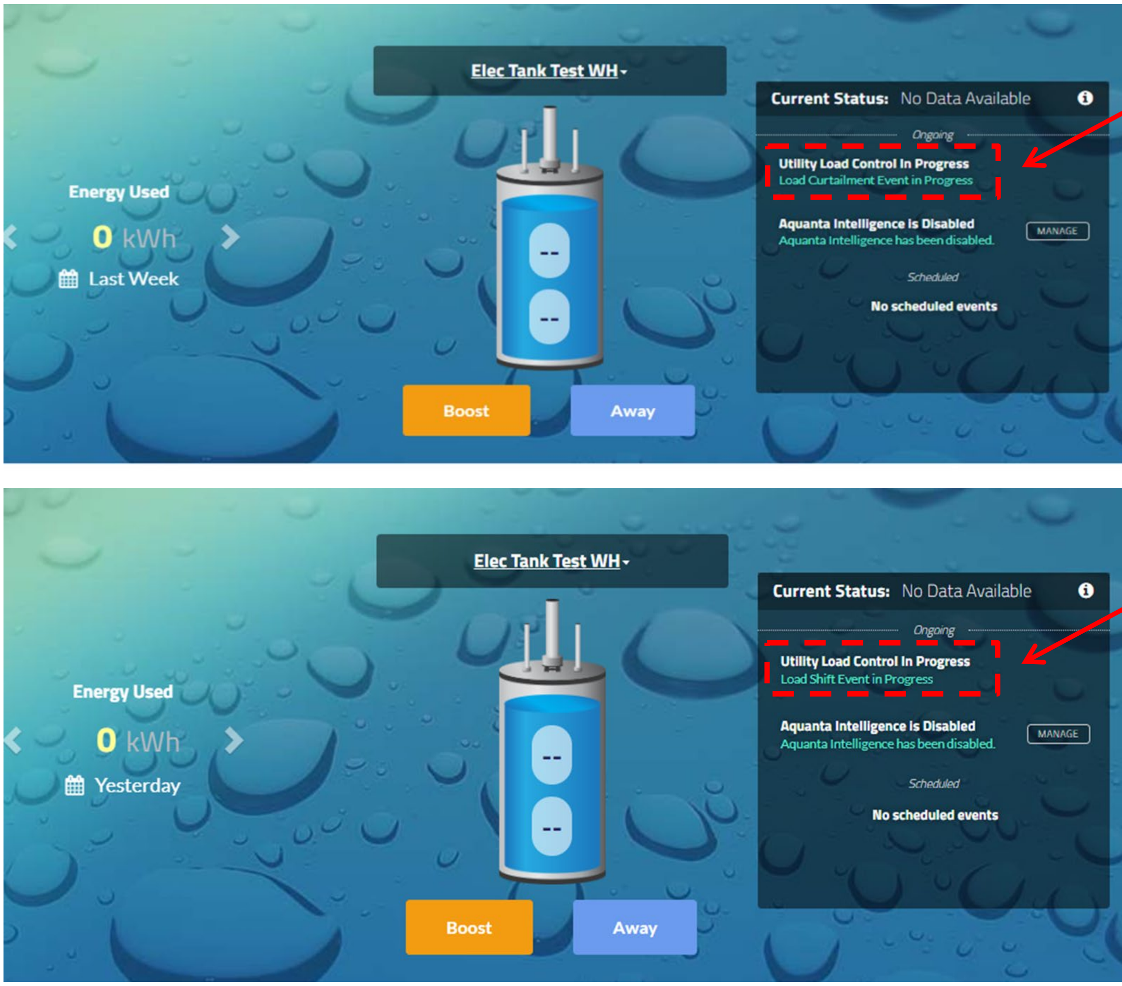


FIGURE 27. USER PORTAL SCREENSHOTS – PT. 7

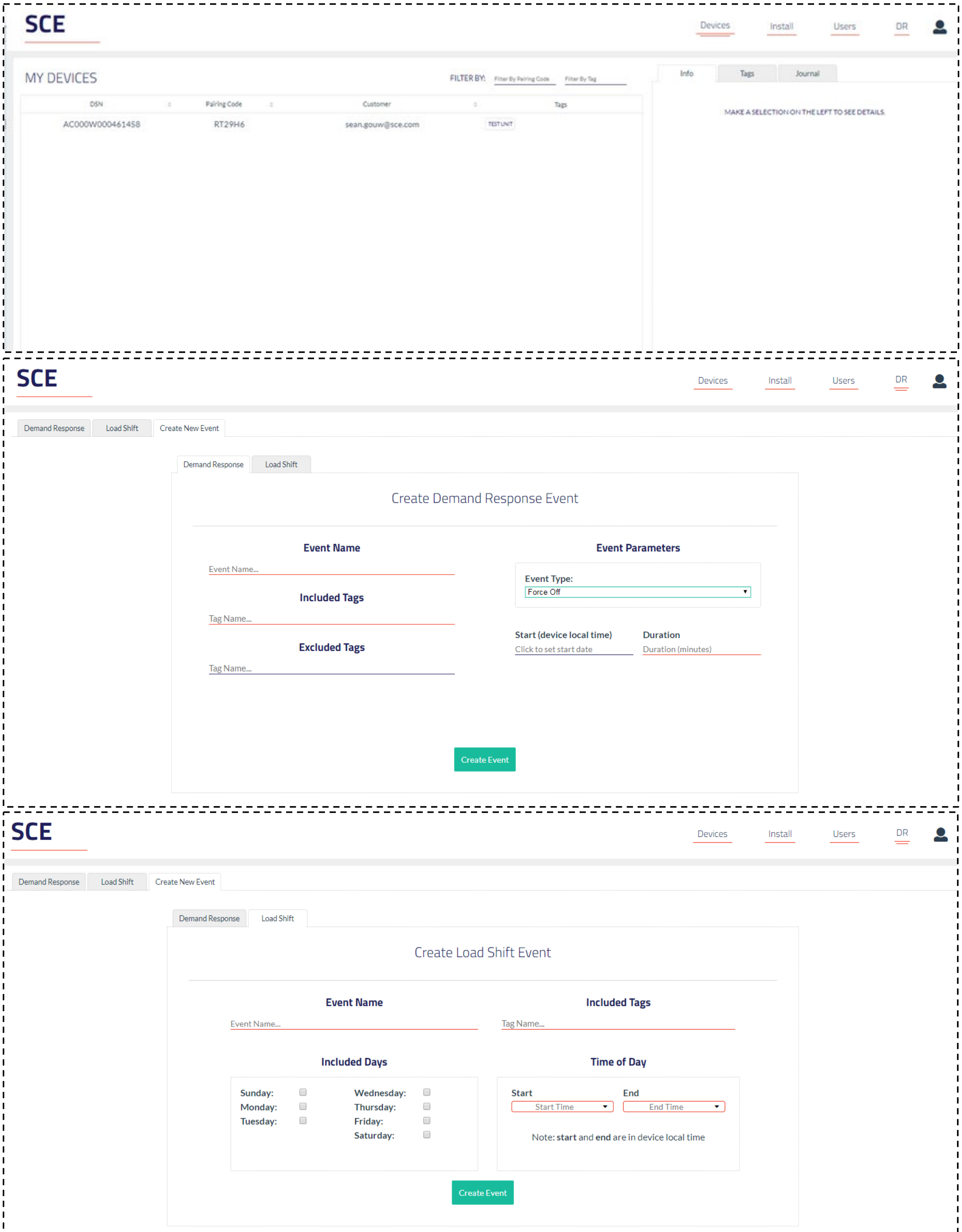


FIGURE 28. FLEET DASHBOARD SCREENSHOTS

Assessment Objectives

This project seeks to conduct laboratory testing of a DR RC on a residential electric resistance storage water heater. Furthermore, this project seeks to inform SCE DR program development with regards to residential water heaters. This laboratory testing activity seeks to accomplish the following:

- Baseline testing of 1 residential water heater
- DR testing of the residential water heater outfitted with the retrofit DR controls, under three DR control schemes:
  - Load Curtailment controls
  - TOU-driven controls
  - Thermal storage/GIWH controls

The following questions are established for the purposes of this laboratory study:

1. What are the demand savings benefits of the identified DR control schemes?
2. What happens to water heater thermal performance for the identified DR control schemes?
   a. What are the maximum/minimum/average water temperatures in the water heater tank under typical usage, with and without the retrofit controls?
   b. Under the DR control schemes, do the retrofit controls maintain water temperatures suitable to continue meeting the needs of typical home water usage?
   c. Do the reduced water temperatures appreciably increase the risk of pathogen growth, such as legionella bacteria?
   d. Do any of the DR control schemes involve elevated water temperatures to increase/optimize energy storage or appreciably increase the risk of scalding water?
3. In terms of customer experience and interaction, what can be expected with the retrofit technology under each of the DR control schemes? Questions may include but are not limited to the following:
   a. Is Automated Demand Response (ADR) available/enabled for this retrofit technology? Explain.
   b. Is the customer interface easy to use? What are the customer options for overriding? Other noteworthy features?

TECHNICAL APPROACH/TEST METHODOLOGY

CALORIMETER CONTROLLED ENVIRONMENT LABORATORY (CCEL)

The Calorimeter Controlled Environment Laboratory (CCEL) is a general purpose test chamber located in SCE's Technology Test Centers (TTC) in Irwindale, CA. The test chamber is suitable for testing a wide range of appliances, plug loads, and electronics. CCEL features electrical connections as well as hot and cold water connections for supply to various test products. Electrical connections are controlled with a voltage regulator to ensure stable tolerances are continuously maintained. CCEL has dedicated humidification, heating and refrigeration systems that allow it to maintain a wide range of conditions needed for product testing. Conditions may be held at stable tolerances or shifted at predetermined profiles. Figure 29 shows the data acquisition and chamber controls as well as the water heater test rig.

Figure 29. CCEL DAQ and Controls (Top Left), Water Heater Test Unit (Top Right), and Water Heater Test Rig (Bottom)

TEST RIG OPERATION & LAYOUT

Figure 30 shows the system diagram of the test setup, where measurement/state points and key components are identified. The test rig is a closed-loop water system. This system contains a top tank (Tank 2) and a bottom tank (Tank 1). Tank 1 has a recirculation loop and is conditioned by Chiller 1. Tank 2 also has a recirculation loop and is conditioned by Chiller 2. The test rig operates in recirculation mode for a majority of the time, where the water heater is isolated from the two recirculation loops, until a water draw is initiated.

When a water draw is initiated, Tank 1 provides conditioned water to the water heater inlet. The water is heated up and transferred to Tank 2. Tank 2 continues to operate in recirculation loop mode, until Chiller 2 is able to significantly pull-down the temperature of the hot water. When significant pull-down has occurred, water is transferred back to Tank 1. For every water draw that is initiated, a proportional control valve (CV1), located on the water heater outlet, throttles flowrates as desired.

Control logic is implemented to ensure that water draws do not occur if Tank 1 levels are too low or Tank 2 levels are too high. If Tank 1 levels are too high, transfers from Tank 2 to Tank 1 are prevented. Transfers from Tank 2 to Tank 1 are also prevented within five minutes before or after water draw events.

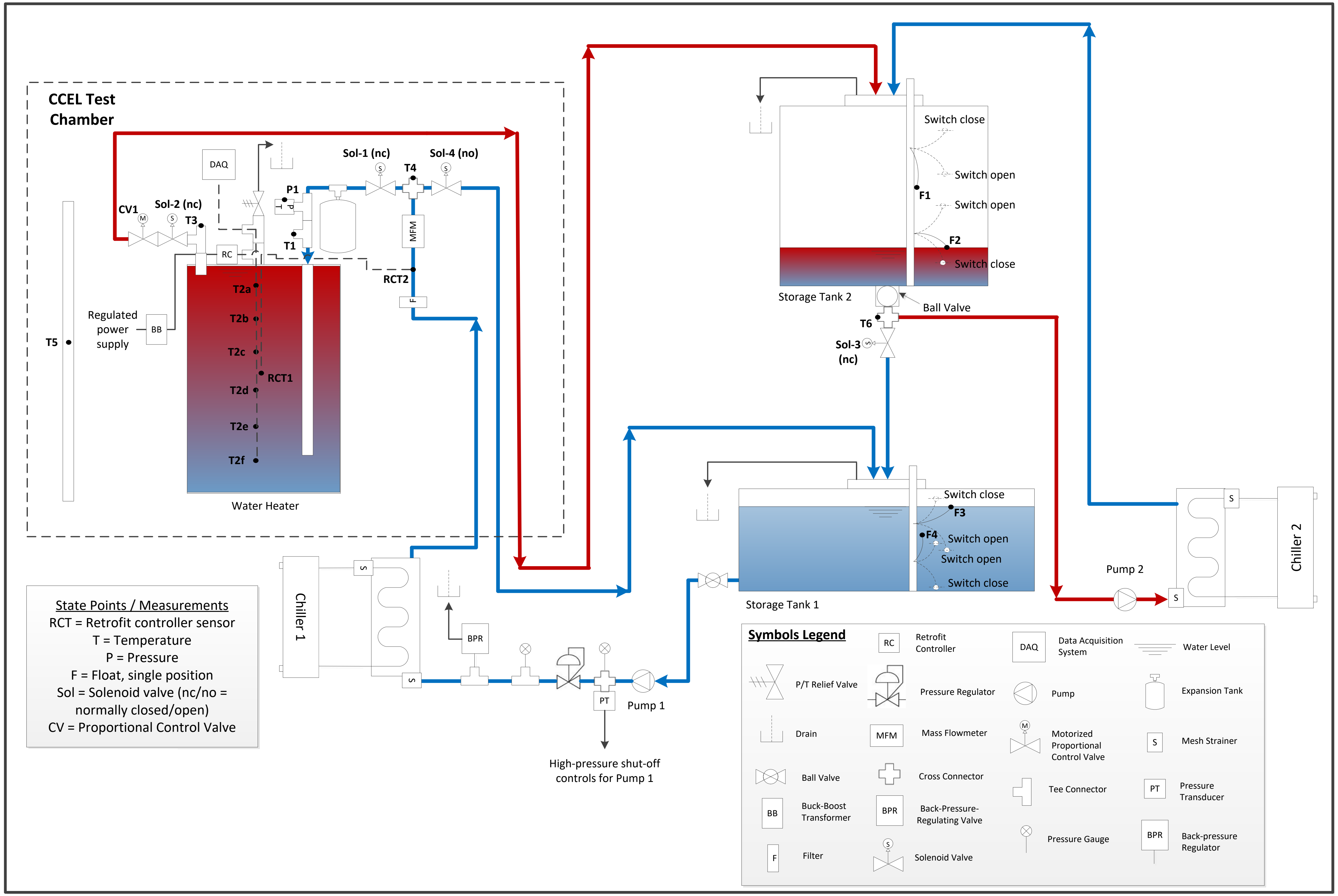


FIGURE 30. WATER HEATER TEST RIG SYSTEM DIAGRAM

INSTALLATION AND INSTRUMENTATION

The water heater and RC were installed and instrumented with guidance from pertinent product literature, and the specifications of the federal test procedure for energy consumption (CFR Title 10 Part 430 Subpart B Appendix E – Uniform Test Method for Measuring the Energy Consumption of Water Heaters). Deviations from the test method were carefully explored and chosen for the purposes of this testing. Table 2 details the instrumentation used for this testing.

TABLE 2. INSTRUMENTATION

MEASUREMENT	MAKE	MODEL	BASIC ACCURACY
Air Temperature	Masy Systems (type-T thermocouples)		±0.32°F
Water Loop, Inlet & Outlet Temperatures	100 ohm platinum resistance temperature detector (RTD)		±0.18°F
Water Heater Tank Temperatures	TC Direct Type K-304 Stainless Steel Sheath		±0.32°F
Water Flow	Omega	FTB4707 Low Flow Liquid Flowmeter	±1% FS
	Omega	DPF701 ratemeter/totalizer	±0.5 LSD of total; 0.01% of the rate ±1.5LSD
Pressure	Setra	C207 Pressure Transducer	Accuracy RSS* (at constant temperature) ±0.13% FS
Electrical	Hioki	3169-21 Power Meter	AC Voltage: ±0.2% rdg. 0.1% FS AC Current: ±0.2% rdg. ±0.1 FS + current sensor accuracy Active Power: ±0.2% FS + current sensor accuracy (at power factor = 1) Clamp on sensor 9661: ±0.3% rdg. ±0.01% FS (different from each sensor models)
	Fluke	I200s AC Current Clamp	1.5% + 0.5A (48-65 Hz) (% reading + floorspec)

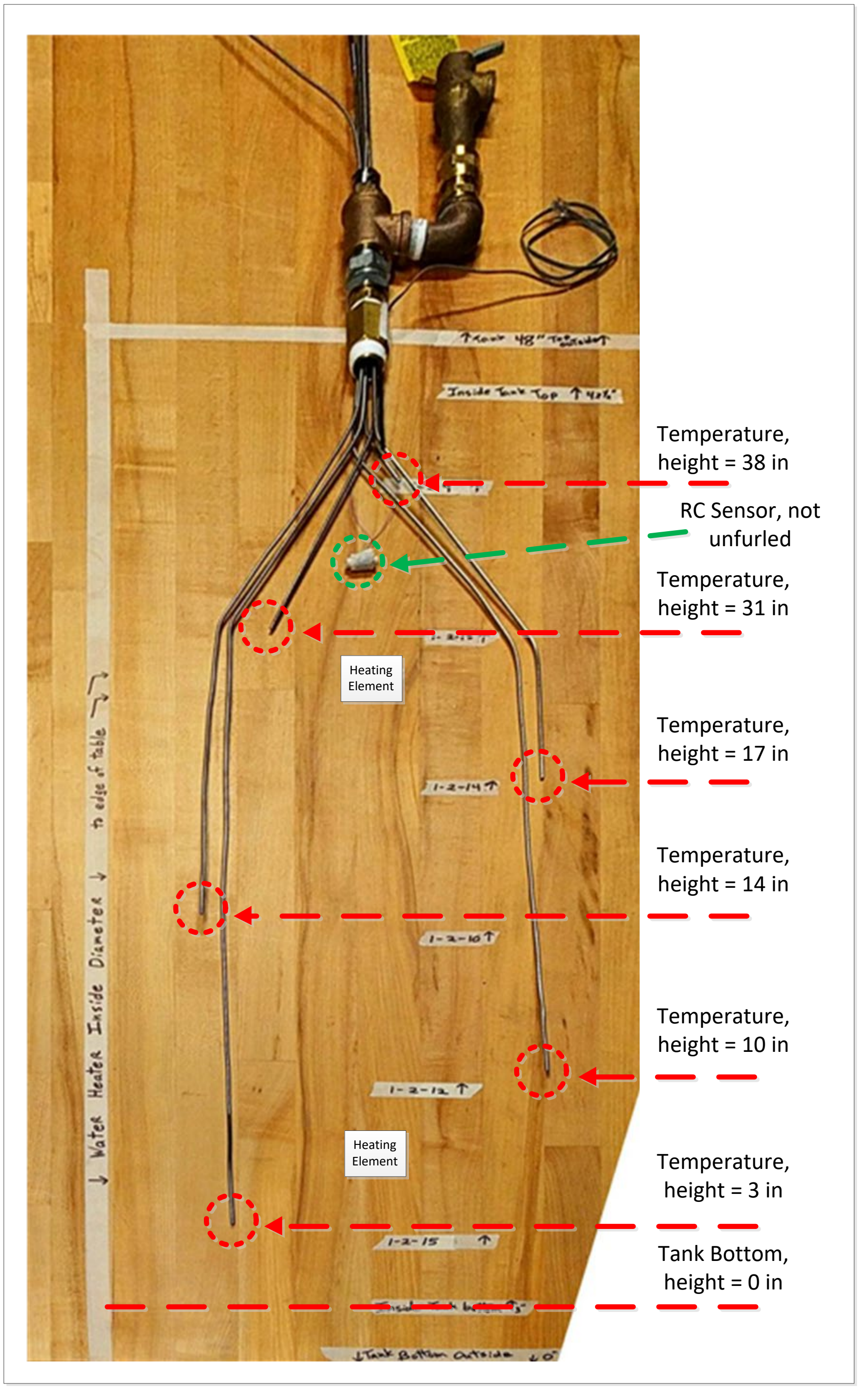


FIGURE 31. WATER HEATER TANK TEMPERATURE SENSOR PLACEMENT MOCK UP

***Note:** The RC is not unfurled in the mock-up. During actual installation, it was allowed to unfurl to the bottom of the tank, as per manufacturer instructions.

TABLE 3. TARGET TEST CONDITIONS

TEST PARAMETER	TARGET CONDITION
Ambient Air Temperature, °F	54 ±2.5
Supply Water Temperature, °F	63 ± 2
Setpoint/Outlet Water Temperature, °F	125 ± 5
Supply Water Pressure, PSIG*	Between 40 and MFR Max.
Supply Voltage	240 ± 2.4 (1%)

***Note:** The water heater test rig maintains pressures during water draw events, but outside of these events in recirculation mode, water heater pressures drop to ambient.

Ambient Air Temperature: The ambient air temperature was chosen as the winter median (December through February) of the Typical Meteorological Year data (TMY3) for Burbank-Glendale-Pasadena (Climate Zone 9) of 54°F with a tolerance of ± 2.5°F.

An ambient air temperature sensor was installed at the vertical midpoint of the water heater and approximately 2 feet (610 mm) from the surface of the water heater.

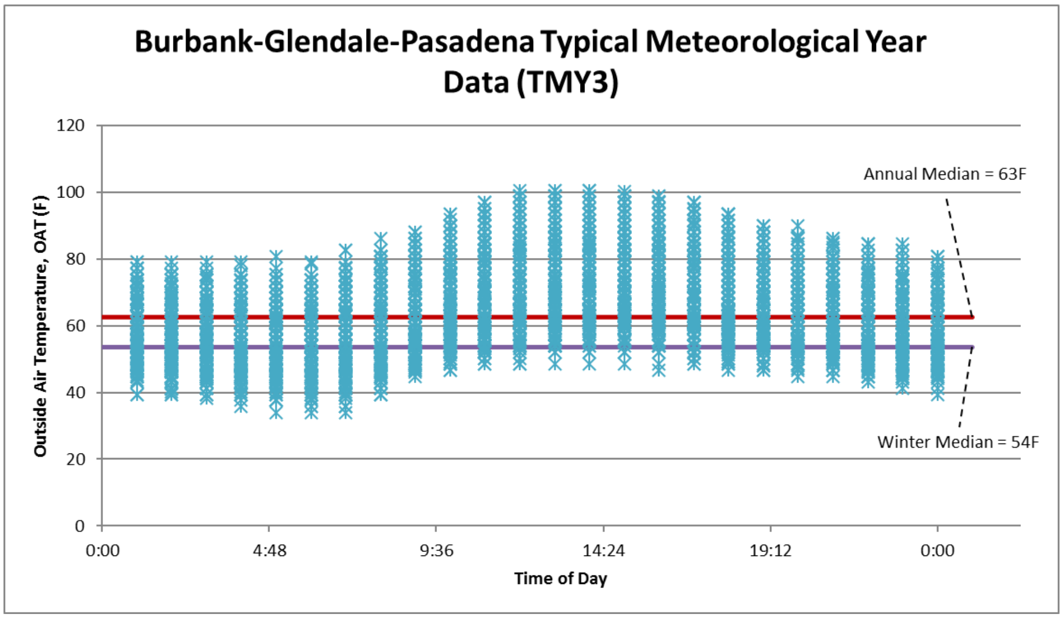


FIGURE 32. BURBANK-GLENDALE-PASADENA TYPICAL METEOROLOGICAL YEAR DATA – TMY3

Supply Water Temperature: The temperature of the water being supplied to the water heater shall was maintained at the winter median (December through February) of the Burbank-Glendale-Pasadena Annual Water Mains Temperatures, of 63°F with a tolerance of ±2°F (14.4°C ±1.1°C) throughout the test.

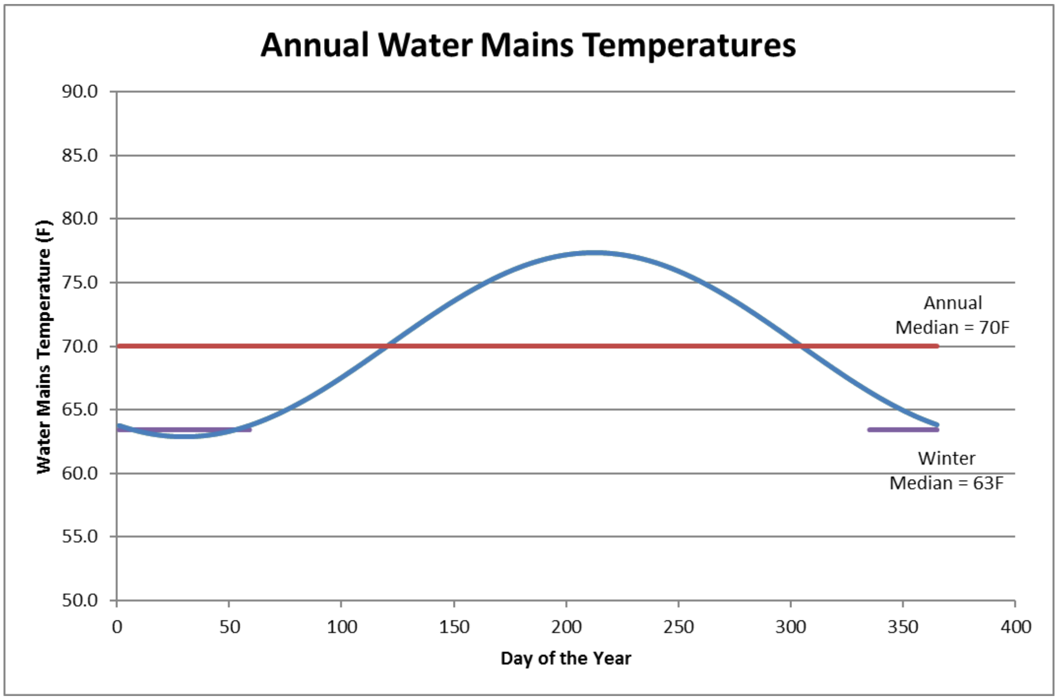


FIGURE 33. BURBANK-GLENDALE-PASADENA ANNUAL WATER MAINS TEMPERATURES

EXPLORING WATER DRAW PROFILES

"CFR Title 10 Chapter II Subchapter D Part 430 Subpart B Appendix E to Subpart B of Part 430—Uniform Test Method for Measuring the Energy Consumption of Water Heaters" is the test procedure for determining the efficiency rating of water heaters sold in the United States. As part of the test method, a water draw pattern is established, according to the size of the water heater. The water heater in this test project typically uses the medium usage draw pattern (total daily draw 55 gallons) as shown in Table 4.

TABLE 4. DOE MEDIUM USAGE HOT WATER DRAW PATTERN

DOE MEDIUM USAGE DRAW PATTERN

DRAW #	TIME DURING TEST [HH:MM]	FLOW RATE (GPM)	DURATION (MIN)	VOLUME (GALLONS
1	0:00	1.7	9	15
2	0:30	1	2	2
3	1:40	1.7	5	9
4	10:30	1.7	5	9
5	11:30	1.7	3	5
6	12:00	1	1	1
7	12:45	1	1	1
8	12:50	1	1	1
9	16:00	1	1	1
10	16:15	1	2	2
11	16:45	1.7	1	1
12	17:00	1.7	4	7

***Duration rounded to the nearest minute.**

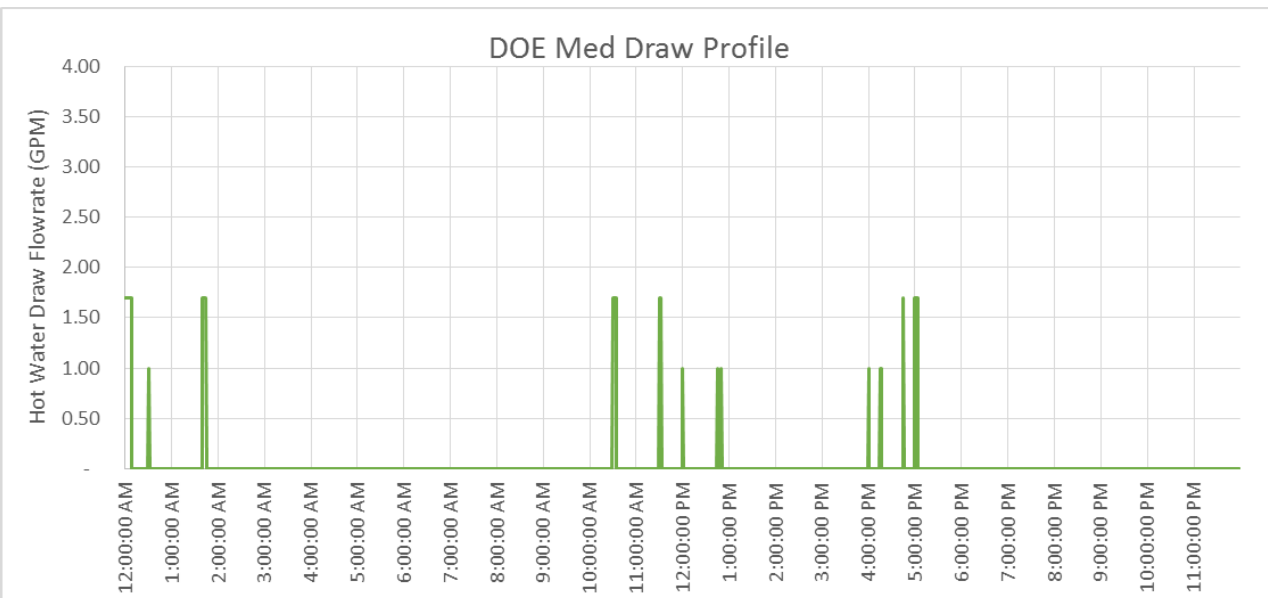


FIGURE 34. DOE MEDIUM USAGE HOT WATER DRAW PATTERN

The U.S. Department of Energy also features the Building America Program, which conducts applied research, development, and deployment in residential buildings. Building America projects are led by U.S. Department of Energy National Laboratories and expert building science teams in partnership with leading industry players. This program provides spreadsheet tools for establishing more realistic annual water usage draw patterns.[15] For the purposes of this project, it was desired to explore a more realistic water draw profile, informed by the Building America Program's spreadsheet tools.

The following excerpt from the accompanying literature[16] gives insight into the tool:

"This paper describes the development of a spreadsheet tool that generates random event profiles based on realistic probability distributions for hot water event duration, flow rate, clustering, individual fixture use, and time between events. It also includes realistic simulation of vacation periods, weekend/weekday effects, geographic location, and seasonality. The assumptions about the profiles were derived from a variety of sources, primarily two residential water use studies conducted by Aquacraft (Aquacraft 2008, Mayer and DeOreo 1999). One of these studies included 1200 houses, but measured total water use only. The other study was a smaller 20-house study that disaggregated hot and cold water events."

The following parameters were chosen for producing a randomized annual water usage profile with the DOE Building America Program's spreadsheet tool:

TABLE 5. HOT WATER EVENT SCHEDULE GENERATOR INPUTS

DHW EVENT SCHEDULE GENERATOR (UPDATED 03/07/13)

Number of Bedrooms	3
DHW Tank Temperature (°F)	125
Temperature of Shower, Sink, and Bath Draw	110
Climate Location (TMY3 Site)	Burbank-Glendale-Pasadena Bob, CA
Time Step (Sec) Does not affect runtime; Flow rates become less realistic at larger timesteps.	60
Relaxation Factor (1.0 recommended) 1.0 = default (runtime up to 1 minute with 4 CPUs) 0.5 = more stringent (runtime up to 1 minute with 4 CPUs)	1.0

[15] https://energy.gov/eere/buildings/building-america-analysis-spreadsheets

[16] https://www.nrel.gov/docs/fy10osti/47685.pdf

Throughout the annual generated profile, there is large variability in daily water draw usage produced in terms of number of events, duration, and water draw flow rates. For the purposes of this testing, two days were chosen to represent a typical weekend and weekday winter draw profile: Sunday-1/14 and Monday-1/15. Additionally, modifications were made to the data to simplify the draw profile and accommodate flow meter limitations:

- Draw events under 0.2 gallons per minute (gpm) fall under the measurable range of the water flow meter, and were removed
- Draw event flow rates were rounded up to the nearest multiple of 0.5 gpm.

These modifications were determined to have minimal impacts on the total daily water drawn for each profile. Daily water drawn for Sunday changed from 51.6 to 52.5 gallons. Daily water drawn for Monday changed from 25.3 to 24.5 gallons. The draw profiles are defined in Table 6, Table 7, and Figure 35.

TABLE 6. SELECTED WATER DRAW SCHEDULE: REPRESENTATIVE WEEKEND PROFILE

SUNDAY (1/14) USAGE DRAW PATTERN

DRAW #	TIME DURING TEST [HH:MM]	FIXTURE	FLOW RATE (GPM)	DURATION (MIN)*	VOLUME (GALLONS)
1	2:20	Sink 2	1	2	2
2	5:44	Kitchen Sink	1	1	1
3	5:46	Sink 3	1.5	3	4.5
4	7:40	Shower 1	2	3	6
5	7:43	Sink 2	0.5	1	0.5
6	7:45	Kitchen Sink	0.5	1	0.5
7	7:57	Kitchen Sink	0.5	1	0.5
8	7:59	Kitchen Sink	0.5	1	0.5
9	8:19	Bath 1	3.5	5	17.5
10	8:44	Kitchen Sink	1.5	1	1.5
11	8:46	Sink 2	1	1	1
12	8:48	Sink 2	0.5	1	0.5
13	12:07	Kitchen Sink	1	1	1
14	15:45	Kitchen Sink	0.5	1	0.5
15	20:41	Clothes Washer	0.5	1	0.5
16	20:46	Clothes Washer	2	1	2
17	20:51	Clothes Washer	1.5	1	1.5
18	21:01	Clothes Washer	3	1	3
19	22:37	Sink 4	0.5	1	0.5
20	22:57	Kitchen Sink	1	1	1
21	23:15	Sink 3	0.5	1	0.5
22	23:37	Shower 1	2	3	6

***Duration rounded to nearest minute**

TABLE 7. SELECTED WATER DRAW SCHEDULE: REPRESENTATIVE WEEKDAY PROFILE

MONDAY (1/15) USAGE DRAW PATTERN

Draw #	Time during test [HH:MM]	Fixture	Flow Rate (gpm)	Duration (min)*	Volume (gallons)
1	0:07	Kitchen Sink	0.5	1	0.5
2	0:08	Shower 1	1.5	1	1.5
3	1:33	Kitchen Sink	0.5	1	0.5
4	7:13	Shower 1	2	3	6
5	9:53	Clothes Washer	1.5	1	1.5
6	10:07	Kitchen Sink	1	1	1
7	10:17	Kitchen Sink	0.5	1	0.5
8	10:19	Kitchen Sink	0.5	2	1
9	11:07	Clothes Washer	1	1	1
10	12:22	Clothes Washer	3	1	3
11	12:33	Kitchen Sink	1	1	1
12	12:56	Clothes Washer	2.5	1	2.5
13	13:36	Clothes Washer	1.5	1	1.5
14	17:00	Sink 4	0.5	1	0.5
15	18:21	Kitchen Sink	0.5	1	0.5
16	21:09	Sink 2	0.5	1	0.5
17	21:11	Kitchen Sink	1.5	1	1.5

***Duration rounded to the nearest minute**

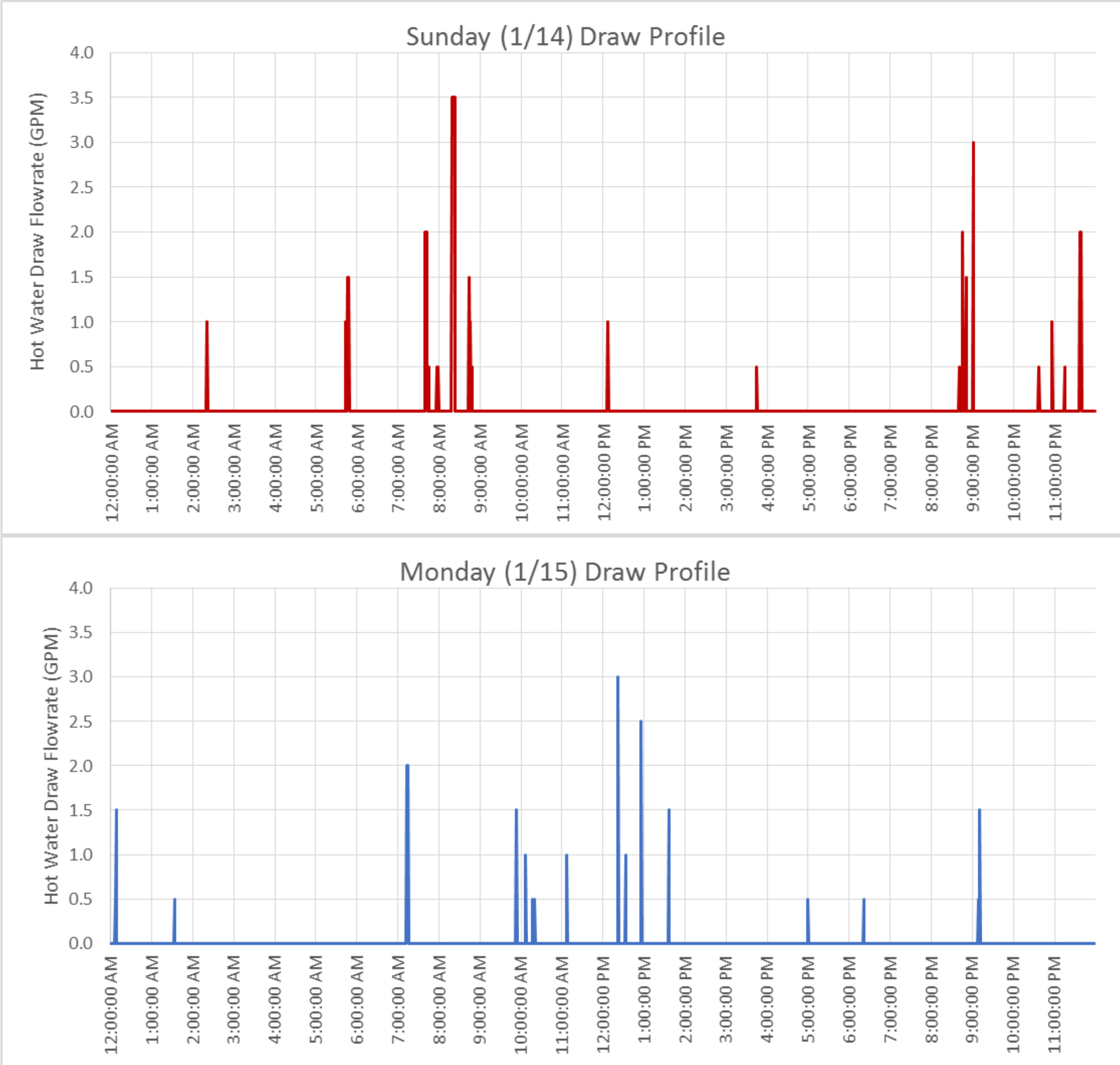


FIGURE 35. SELECTED WATER DRAW SCHEDULES: REPRESENTATIVE WEEKEND AND WEEKDAY PROFILES

TEST SCENARIOS

Table 8 shows the test scenarios, descriptions, and draw profiles that were chosen for laboratory investigation.

TABLE 8. TEST SCENARIOS

TEST #		DESCRIPTION	DRAW PROFILE
1	a	Base-weekday	Monday
	b	Base-weekday-repeat	
	c	Base-weekday-repeat	
2	a	Base-weekend	Sunday
	b	Base-weekend-repeat	
	c	Base-weekend-repeat	
3		Base-weekday-retrofit controller active	Monday
4	a	Load Curtailment-weekday	
	b	Load Curtailment-weekday	
5	a	TOU-DA-weekday	
	b	TOU-DA-weekday-repeat	
6	a	TOU-DA-weekend	Sunday
	b	TOU-DA-weekend-repeat	
7	a	GIWH-weekend	
	b	GIWH-weekend-repeat	

TEST PROCEDURES

RETROFIT CONTROLLER OUTPUTS

SCE worked with the manufacturer to acquire and corroborate key retrofit controller outputs with measurements/calculations obtained with independent lab instrumentation. (This monitoring data is not available through the user portal or fleet dashboard interfaces.). The following outputs were provided:

- Temperature setpoint
- Top tank temperature
- Cold water supply temperature*

  The manufacturer indicated that cold water temp data was not active during testing. One data point appeared to be set at 62.6°F.
- Energy transfer due to heating, heat loss, and hot water usage

BASELINE TESTING (TESTS 1-3):

The water heater was operated with the retrofit controller disabled, for six 24-hr tests, where three 1/14-Sunday and four 1/15-Monday draw profiles were used (Tests 1a – 1c and Tests 2a – 2c). Water heater performance was monitored.

Additionally, one baseline test was conducted with the retrofit controller active, but learning functions disabled (Test 3). The 1/15-Monday draw profile was used. Water heater performance was monitored.

Typically, the hot water usage learning functions of the retrofit controller require an initial learning period anywhere from 2 – 10 days. The impacts of this learning are primarily efficiency-focused, and are reported to have little to no impact on DR operation. The learning period was not implemented and its effects were not studied for the purposes of this testing.

LOAD CURTAILMENT CONTROLS TESTING (TEST 4):

Two 24-hr tests were run, with a scheduled 2-hr load curtailment event occurring at 6:00 PM to 8:00 PM. The temporary load curtailment event was initiated via the controller's Fleet Dashboard. The 1/15-Monday draw profile was used. Water heater performance was monitored and corroborated with the retrofit controller's outputs.

TOU-DA-DRIVEN CONTROLS TESTING (TESTS 5-6):

Four 24-hr tests were run, with the controller programmed to TOU controls, configured for two TOU pricing schedules: TOU-DA-weekdays (winter) & TOU-DA-weekends (winter). The 1/15-Monday draw profile was used with the TOU-DA-weekday (winter) schedule, and the 1/14-Sunday draw profile was used with the TOU-DA-weekend (winter) schedule. Water heater performance was monitored and corroborated with the retrofit controller's outputs.

GRID-INTERACTIVE WATER HEATER (GIWH) CONTROLS TESTING (TEST 7):

Two 24-hr tests were run. The water heater with retrofitted controls was subjected to the 1/14-Sunday draw profile. GIWH specific controls are not currently commercially available. SCE will work with the manufacturer to adjust controls in a manner reasonably representative of one that invokes an energy storage strategy during an overgeneration event. The overgeneration event is considered to be the time period between 10:00 AM – 4:00 PM[17].

From the Fleet Dashboard interface, two “Load Shift” events are created, one from 12:00 AM – 10:00 AM, and another from 4:00 PM – midnight. From the end-user portal, “Boost” mode is scheduled to occur from 9:00 AM – 4:00 PM. The end-user portal does not allow boost mode scheduling from 10:00 AM – 4:00 PM, but the “Load Shift” event should override Boost mode from 9:00 AM until 10:00 AM. Water heater performance was monitored and corroborated with the retrofit controller’s outputs.

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[17] CAISO time-of-use periods analysis, January 22, 2016. 10 AM – 4 PM is the “Super Off Peak” period for January, weekends, as per CAISO proposed weekday and weekend/holiday TOU periods. http://docs.cpuc.ca.gov/PublishedDocs/Efile/G000/M157/K905/157905349.PDF

EQUATIONS

The following equations were implemented for the various reported parameters of this section. Equations were applied in spreadsheets, using data sampled at one-second intervals.

GENERAL

Equation 1 is the equation for a running total. For a given parameter of interest, each value is added to the running sum of the values that occurred before it, starting with the first value that occurred at the beginning of the 24-hour test period.

EQUATION 1. RUNNING TOTAL

$$\boldsymbol{Running\ Total} = \boldsymbol{Value_{t=0}} + \boldsymbol{Value_{t=1}} + \cdots$$

Equation 2 is the formula for percent deviation. A parameter of interest in a given test scenario (Value 1) is benchmarked to the corresponding parameter from the chosen baseline (Value 2). The baseline for tests using the weekday (Monday) draw profile is Test 1a. The baseline for tests using the weekend (Sunday) draw profile is Test 2a.

EQUATION 2. % DEVIATION

$$\%\ \boldsymbol{Deviation} = \frac{\boldsymbol{Value_1} - \boldsymbol{Value_2}}{\boldsymbol{Value_2}}$$

Equation 3 is the formula for approximating the total volume of hot water delivered by the water heater, during a 24-hour test period. For every hot water draw event, the average measured volumetric flowrate is multiplied by the defined event time. The volumes are summed for all events that occurred during the 24-hour test period.

EQUATION 3. HOT WATER VOLUME DELIVERED

$$\boldsymbol{HWVD} = \sum_{m=1}^{m} \dot{V}_m * \Delta t_m$$

Where

$\boldsymbol{HWVD}$=Total hot water volume delivered (gal)

$\boldsymbol{m}$= water draw event, as defined in the Monday or Sunday draw profiles (22 events for Sunday profile, 17 events for Monday draw profile)

$\dot{V}_m$= Volumetric flow of water during hot water draw event (gal/min)

Δt_m= Duration of hot water draw event (min)

ENERGY

The retrofit controller reports three types of energy (in units of W-h): energy added by heating, energy lost by hot water usage, and standing losses. It is of interest to corroborate these values based on independent lab measurements. Looking at the overall net energy of the water heater, two different equation forms of net energy are explored.

Equation 4 is the first form used for calculating net energy of the water heater. Form 1 treats the water heater as a fixed volume of hot water and analyzes the change in energy via the transient changes in median tank temperature. Changes in median temperature occur anytime cold water displaces hot water through usage, cools from standing losses, or heats from the heating elements.

EQUATION 4. NET ENERGY, FORM 1

$$E_{F1-NER} = C_1 * \rho * V * C_P * (T_{n-1} - T_n)$$

Where

C_1 = Conversion factor (0.293 W-h / Btu)

E_{F1-NER} = Net energy, equation form 1 (W-h)

ρ = Density of water (assumed constant, 62 lb/ft^3)

V= Volume of water tank (36 gallon = 4.81 ft^3)

C_P = Specific heat capacity of water (assumed constant, 1 Btu/lb-°F)

T_n = Median Water Heater Tank Temperature at time of "n" sec (°F)

T_{n-1} = Median Water Heater Tank Temperature at prior time of "n-1" sec (°F)

Equation 5 is the second form used for calculating net energy of the water heater. Form 2 of the net energy equation incorporates the sum of three separately calculated energy values.

EQUATION 5. NET ENERGY, FORM 2

$$E_{F2-NER} = E_{heat} - E_{loss} - E_{use}$$

Where

E_{F2-NER} = Net energy, equation form 2 (W-h)

E_{heat}= Energy added by heating element (W-h)

E_{loss}= Standing heat losses to ambient space (W-h)

E_{use}= Energy lost by hot water usage (W-h)

Equation 6 is the equation for finding energy added from the heating elements of the water heater. Heating energy is approximated as the power input to the water heater, multiplied by the sampling interval, and converted to W-h.

EQUATION 6. ENERGY FROM HEATING

$$E_{heat} = C_2 * P * \Delta t$$

Where

C_2 = Conversion factor (1 h/3,600 sec)

P = Measured water heater power (Watts)

Δt = sampling interval (1 sec)

The energy of standing heat losses is calculated by multiplying the heat loss rate by the data recording interval of one second. The heat loss rate is approximated with the temperature difference between the median tank temperature and ambient space temperature, multiplied by an assumed overall heat transfer coefficient and effective heat exchange area (the UA value).

EQUATION 7. ENERGY OF STANDING HEAT LOSSES

$$E_{loss} = C_1 * UA * (T_n - T_{A,n}) * \Delta t * C_2$$

Where

C_1 = Conversion factor (0.293 W-h/Btu)

UA = Heat transfer coefficient & heat transfer area (assumed 2.87 Btu/h-°F) [18]

T_n = Median Water Heater Tank Temperature at time of "n" seconds (°F)

$T_{A,n}$ = Ambient Temperature at time of "n" seconds (°F)

Δt = sampling interval (1 sec)

C_2 = Conversion factor (1 h/3,600 **sec)**

Energy lost from hot water usage is approximated by calculating the difference in energy between the volumes of hot water exiting the water heater and volumes cold water entering the water heater.

EQUATION 8. ENERGY LOST BY HOT WATER USAGE

$$E_{use} = C_1 * \rho * \dot{V} * \Delta t * C_P * (T1 - T3)$$

Where

C_1 = Conversion factor (0.293 W-h/Btu)

ρ = Density of water (assumed constant, 62 lb/ft^3)

$\dot{V}$= Volumetric flow of water during hot water draws (ft^3/sec)

Δt = sampling interval (1 sec)

C_P = Specific heat capacity of water (assumed constant, 1 Btu/lb-°F)

$T1$ = Water heater inlet temperature (°F)

$T3$ = Water heater outlet temperature (°F)

[18] The particular UA value for the test water heater was not available. The UA value from Table 10, reported UA value for water heaters, Increased Insulation (2.5" — R20 Foam). https://aceee.org/files/proceedings/1998/data/papers/0114.PDF

RESULTS & DISCUSSION

All data tables and figures are presented with observations and brief discussions. For the following data tables, benchmarks are highlighted in green. Certain percent deviations and their corresponding values are also highlighted: deviations at or above 5% are highlighted in yellow, deviations at or above 20% are highlighted in red.

ALL TESTS: DAILY ANALYSIS WINDOW

TABLE 9. ALL TESTS, DATA AND DEVIATIONS – DAILY ANALYSIS WINDOW

Draw Profile	Date of Test	Test #		Description	24-Hr Daily Analysis Window: Energy (kWh)	Heating Element Runtime (min)	WH Tank Avg Median Temp (F)	WH Tank Median Temp - Start (F)	WH Tank Median Temp - End (F)	Retrofit Controller Top Tank Temp (F)	T4-Loop Avg Temp (F)	T5-Amb Avg Temp (F)	Hot Water Vol Delivered (gal)
Monday	4/10/2018	1	a	Base-weekday	4.33	56.0	121.9	119.6	122.5	-	62.6	54.1	24.6
	4/11/2018		b	Base-weekday-repeat	4.48	57.8	122.9	122.5	122.8	-	62.6	54.0	24.3
	4/13/2018		c	Base-weekday-repeat	4.35	56.1	122.0	120.7	122.4	-	62.4	54.1	24.7
	4/18/2018	3	-	Base, Ret Ctrl On	4.48	57.8	122.3	120.9	122.1	107.6	62.4	54.1	24.3
	4/19/2018	4	a	Load Curtailment-weekday	4.48	57.8	122.4	122.1	122.8	107.6	62.4	54.0	24.5
	4/20/2018		b	Load Curtailment-weekday-repeat	4.47	57.8	122.6	122.8	123.2	107.9	62.5	54.0	24.6
	4/21/2018	5	a	TOU-DA-weekday	4.26	54.9	122.4	123.2	121.4	107.7	62.5	54.0	24.5
	4/22/2018		b	TOU-DA-weekday-repeat	4.39	56.7	122.0	121.4	121.5	107.4	62.6	54.0	24.3
Sunday	4/14/2018	2	a	Base-weekend	7.95	103.7	120.3	122.4	122.4	-	62.5	54.1	52.4
	4/15/2018		b	Base-weekend-repeat	7.96	103.9	120.2	122.4	122.5	-	62.5	54.1	51.1
	4/16/2018		c	Base-weekend-repeat	7.41	96.6	120.3	122.5	122.5	-	62.5	54.1	47.2
	4/24/2018	6	a	TOU-DA-weekend	7.86	102.2	119.0	122.4	122.5	105.4	62.7	54.0	51.3
	4/25/2018		b	TOU-DA-weekend-repeat	7.92	103.0	118.6	122.5	123.6	105.1	62.6	54.0	51.6
	4/26/2018	7	a	GIWH-weekend	6.88	89.3	117.5	123.6	116.3	104.3	62.6	54.0	52.2
	4/27/2018		b	GIWH-weekend-repeat	7.27	94.5	116.0	116.3	116.1	102.7	62.5	54.0	52.6

Draw Profile	Date of Test	Test #		Description	24-Hr Daily Analysis Window: Energy (% Dev)	Heating Element Runtime (% Dev)	WH Tank Avg Median Temp (% Dev)	WH Tank Median Temp - Start (% Dev)	WH Tank Median Temp - End (% Dev)	Retrofit Controller Top Tank Temp (% Dev)	T4-Loop Avg Temp (% Dev)	T5-Amb Avg Temp (% Dev)	Hot Water Vol Delivered (% Dev)
Monday	4/10/2018	1	a	Base-weekday						-			
	4/11/2018		b	Base-weekday-repeat	3%	3%	1%	2%	0%	-	0%	0%	-2%
	4/13/2018		c	Base-weekday-repeat	0%	0%	0%	1%	0%	-	0%	0%	0%
	4/18/2018	3	-	Base, Ret Ctrl On	3%	3%	0%	1%	0%	-	0%	0%	-1%
	4/19/2018	4	a	Load Curtailment-weekday	3%	3%	0%	2%	0%	-	0%	0%	0%
	4/20/2018		b	Load Curtailment-weekday-repeat	3%	3%	1%	3%	1%	-	0%	0%	0%
	4/21/2018	5	a	TOU-DA-weekday	-2%	-2%	0%	3%	-1%	-	0%	0%	-1%
	4/22/2018		b	TOU-DA-weekday-repeat	1%	1%	0%	1%	-1%	-	0%	0%	-1%
Sunday	4/14/2018	2	a	Base-weekend						-			
	4/15/2018		b	Base-weekend-repeat	0%	0%	0%	0%	0%	-	0%	0%	-2%
	4/16/2018		c	Base-weekend-repeat	-7%	-7%	0%	0%	0%	-	0%	0%	-10%
	4/24/2018	6	a	TOU-DA-weekend	-1%	-1%	-1%	0%	0%	-	0%	0%	-2%
	4/25/2018		b	TOU-DA-weekend-repeat	0%	-1%	-1%	0%	1%	-	0%	0%	-1%
	4/26/2018	7	a	GIWH-weekend	-14%	-14%	-2%	1%	-5%	-	0%	0%	0%
	4/27/2018		b	GIWH-weekend-repeat	-9%	-9%	-4%	-5%	-5%	-	0%	0%	0%

Observations: Table 9 (All tests)

- For weekday baseline Tests 1b, 1c, and 3, energy use and heating element runtimes, deviations were within 3% of Test 1a.
  - Total daily hot water volumes delivered for Tests 1b, 1c, and 3, were within 2% deviation of Test 1a.
- Weekend baseline Tests 2a and 2b had equivalent energy use and heating element runtimes. Test 2c had -7% deviations of both energy use and heating element runtime, compared to Test 2a.
  - Total hot water volume delivered was 10% low for Test 2c, compared to Test 2a.
- For load curtailment Tests 4a and 4b and TOU controls Tests 5a, 5b, 6a, and 6b deviations in energy use/heating element runtimes were within 3% of their respective benchmarks (Tests 1a and 2a).
- For baseline, load curtailment, and TOU controls Tests 1b-6b, the deviations of daily average median tank temperatures were within 1% of their respective benchmarks (Tests 1a and 2a).
  - GIWH Tests 7a and 7b, daily average median tank temperatures saw deviations of -2% and -4%, compared to Test 2a.
- For baseline, load curtailment, and TOU controls Tests 1-6, starting and ending median tank temperatures saw deviations within 3% of their respective benchmarks (Tests 1a and 2a).
  - GIWH Tests 7a and 7b, starting and ending median tank temperatures saw deviations within 5%, compared to test 2a.
- Retrofit controller temperature readings were low compared to lab readings.
  - Low readings may be due to air pocket in T&P valve retrofit fitting that contained RC temperature sensor.
- Consistent T4 cold water supply and T5 ambient temperature averages were maintained for all tests.

Discussion: Table 9 (All tests)

Consistent ambient air temperatures and cold water loop temperatures were maintained throughout all tests. Baseline tests generally demonstrate reasonable repeatability of tank temperatures, water heater daily energy consumption, and total hot water delivered. However, there appeared to be a possible malfunction during Test 2c that resulted in reduced total hot water delivery. The activation of the retrofit controller in Test 3 did not result in meaningful deviations in the 24-hour metrics observed.

Load curtailment (Tests 4a and 4b) and TOU controls (Tests 5a, 5b, 6a, and 6b) had no appreciable impact on daily energy consumption, as deviations were within what was observed for baseline testing. The GIWH controls resulted in reduced daily average median tank temperatures and reduced energy consumption.

BASELINE REPEATABILITY TESTING: WEEKDAY PROFILE

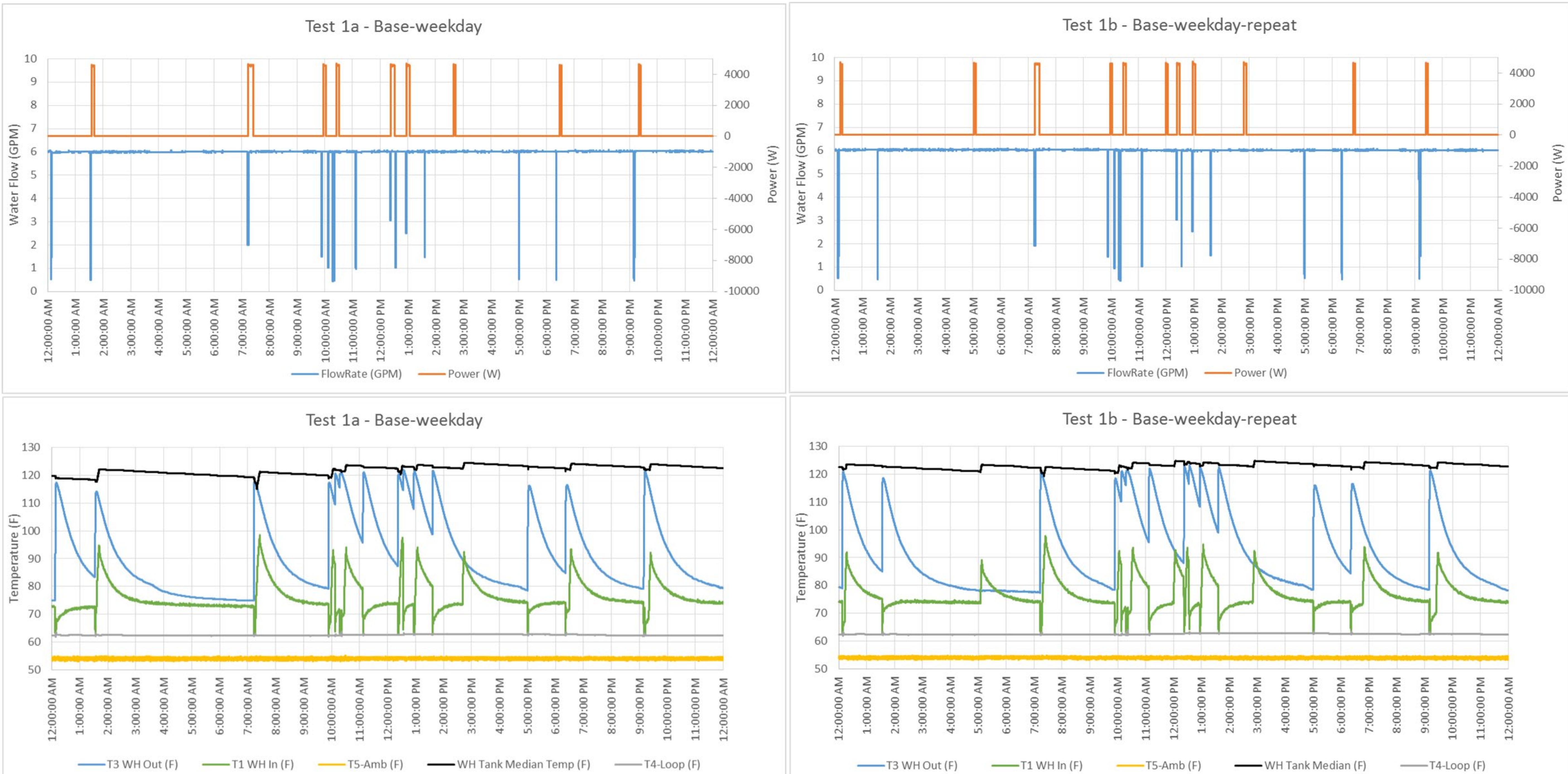


FIGURE 36. POWER, FLOW, AND TEMPERATURES - BASELINE WEEKDAY TESTS 1A AND 1B

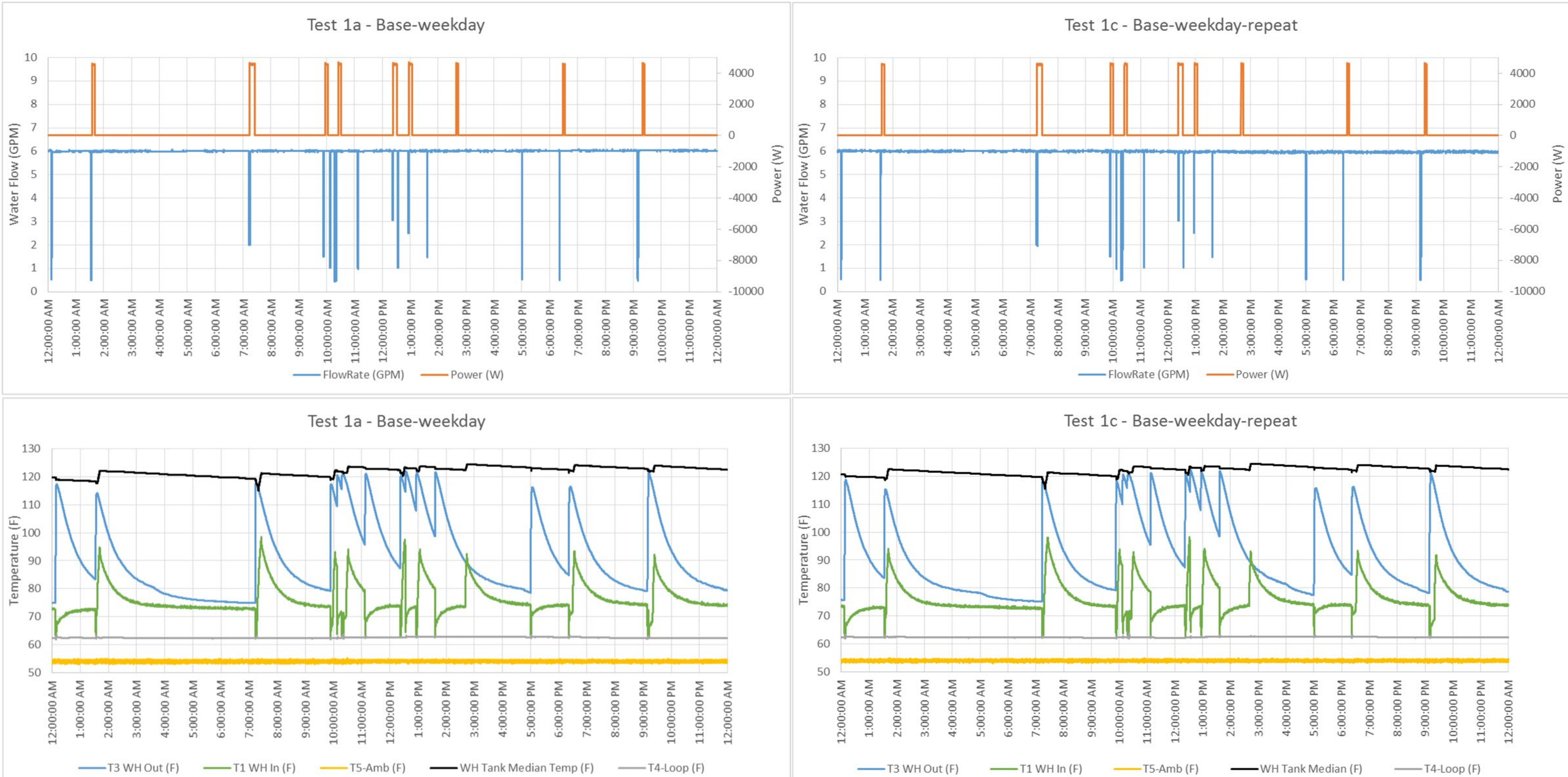


FIGURE 37. POWER, FLOW, AND TEMPERATURES - BASELINE WEEKDAY TESTS 1A AND 1C

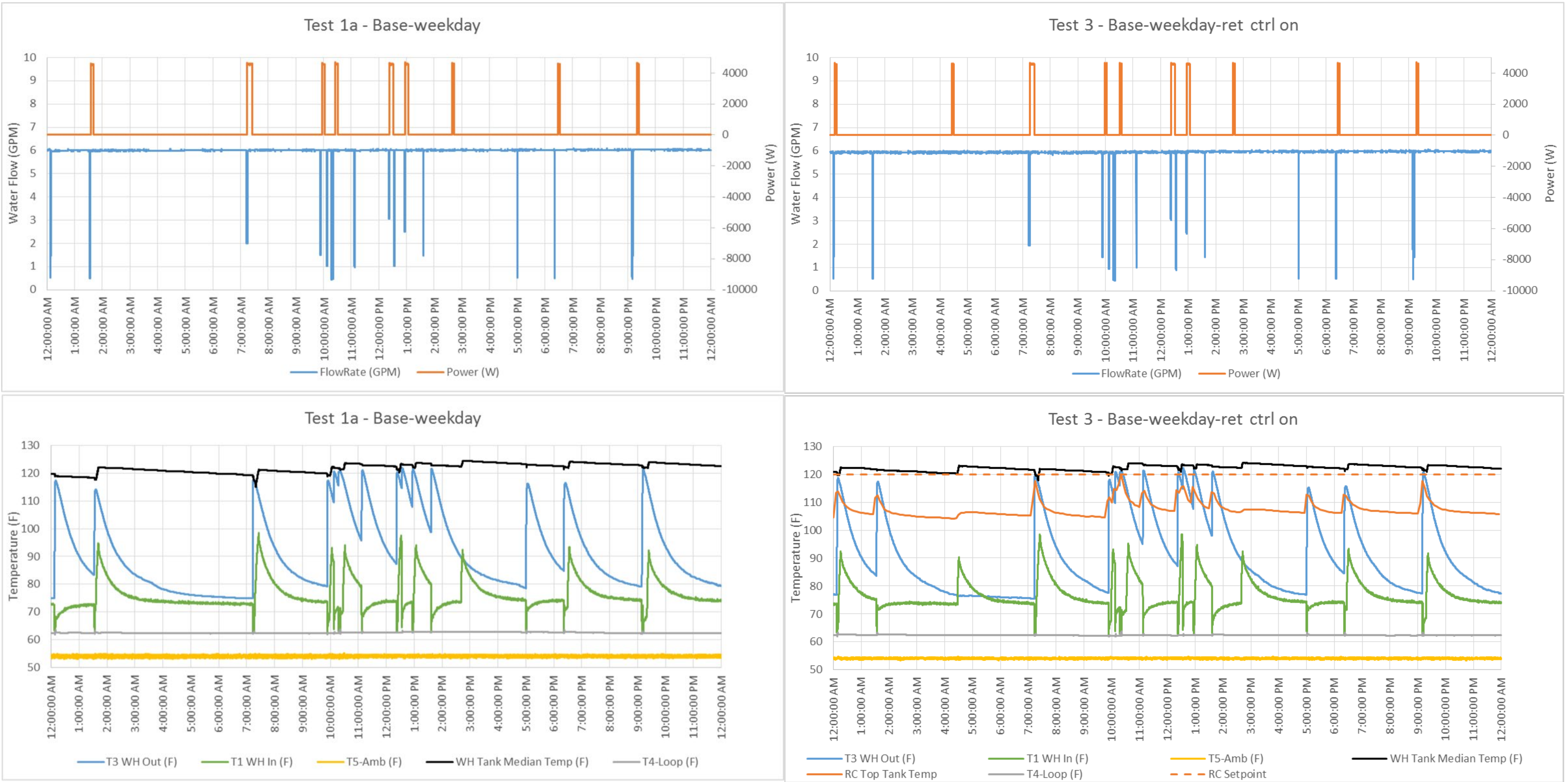


FIGURE 38. POWER, FLOW, AND TEMPERATURES - COMPARING BASELINE WITH RETROFIT CONTROLS ON TESTS 1A AND 3

TABLE 10. BASELINE REPEATABILITY DATA AND % DEVIATIONS – PER-HOT WATER DRAW EVENT ANALYSIS WINDOW ON TESTS 1A, 1B, 1C AND 3 (WEEKDAY PROFILE)

Monday Draw Profile				1a	1b	1c	3	1a	1b	1c	3	1a	1b	1c	3	1a	1b	1c	3
Draw	Dur (min)	Time	Target GPM	Avg Flow Rate (GPM)				T1 WH In Avg Temp (F)				T3 WH Out Avg Temp (F)				WH Tank Avg Median Temp (F)			
1	1	12:07 AM	0.5	0.55	0.55	0.57	0.56	63.8	64.0	63.9	63.9	88.1	107.3	93.2	90.6	119.6	122.4	120.7	120.7
2	1	12:08 AM	1.5	1.46	1.46	1.43	1.47	62.4	62.4	62.3	62.4	113.0	119.8	115.2	114.6	119.2	122.1	120.5	120.4
3	1	1:33 AM	0.5	0.54	0.50	0.56	0.56	63.6	64.2	63.7	64.2	105.2	110.2	105.3	107.3	118.3	122.7	119.3	121.7
4	3	7:13 AM	2	2.00	1.90	1.97	1.95	63.0	63.0	62.9	63.0	115.2	118.0	115.1	117.3	118.4	121.5	118.8	120.7
5	1	9:53 AM	1.5	1.51	1.44	1.50	1.45	63.9	63.8	63.1	63.8	110.2	110.8	114.7	109.7	119.7	120.9	119.7	120.6
6	1	10:07 AM	1	1.02	0.95	0.98	0.96	67.7	67.2	67.6	67.5	118.3	118.8	118.6	118.6	122.1	122.9	122.1	122.7
7	1	10:17 AM	0.5	0.48	0.48	0.51	0.49	64.3	64.1	64.2	64.1	119.1	119.7	119.1	119.6	121.8	122.5	121.7	122.3
8	2	10:19 AM	0.5	0.47	0.50	0.52	0.48	63.5	63.5	63.3	63.4	120.9	121.4	120.8	121.3	121.5	122.2	121.5	122.0
9	1	11:07 AM	1	0.99	1.01	1.03	1.00	65.2	63.9	65.3	65.4	115.8	119.7	115.9	115.8	123.2	123.6	123.1	123.6
10	1	12:22 PM	3	3.07	3.05	3.04	3.02	64.0	65.3	63.7	63.8	114.7	117.8	115.2	115.1	122.0	124.2	122.0	122.5
11	1	12:33 PM	1	1.03	1.02	1.04	0.92	69.7	67.6	69.7	69.6	120.5	122.0	120.6	120.8	123.2	124.1	123.3	123.4
12	1	12:56 PM	2.5	2.50	2.52	2.49	2.49	64.3	64.0	64.0	64.0	119.2	120.8	119.5	119.6	122.8	123.4	122.6	122.8
13	1	1:36 PM	1.5	1.47	1.50	1.48	1.45	65.8	65.5	65.8	65.5	117.4	119.0	117.5	116.4	123.3	123.7	123.2	123.2
14	1	5:00 PM	0.5	0.55	0.55	0.57	0.56	64.1	64.2	64.2	64.1	94.6	93.9	92.8	92.5	123.1	123.5	123.1	122.8
15	1	6:21 PM	0.5	0.54	0.53	0.55	0.56	64.1	64.0	64.0	64.1	99.2	98.6	98.8	98.6	122.3	122.6	122.3	121.9
16	1	9:09 PM	0.5	0.53	0.53	0.55	0.55	64.0	63.9	63.9	64.0	95.5	95.6	93.6	92.1	122.7	123.0	122.4	122.2
17	1	9:11 PM	1.5	1.47	1.48	1.49	1.45	64.1	64.1	64.0	64.0	120.2	120.3	119.7	119.5	122.4	122.7	122.2	121.9

Monday Draw Profile				1a	1b	1c	3	1a	1b	1c	3	1a	1b	1c	3	1a	1b	1c	3
Draw	Dur (min)	Time	Target GPM	Avg Flow Rate (% Dev)				T1 WH In Avg Temp (% Dev)				T3 WH Out Avg Temp (% Dev)				WH Tank Avg Median Temp (% Dev)			
1	1	12:07 AM	0.5		-1%	3%	1%		0%	0%	0%		22%	6%	3%		2%	1%	1%
2	1	12:08 AM	1.5		0%	-2%	1%		0%	0%	0%		6%	2%	1%		2%	1%	1%
3	1	1:33 AM	0.5		-7%	3%	3%		1%	0%	1%		5%	0%	2%		4%	1%	3%
4	3	7:13 AM	2		-5%	-1%	-2%		0%	0%	0%		2%	0%	2%		3%	0%	2%
5	1	9:53 AM	1.5		-4%	-1%	-4%		0%	-1%	0%		1%	4%	0%		1%	0%	1%
6	1	10:07 AM	1		-7%	-4%	-6%		-1%	0%	0%		0%	0%	0%		1%	0%	0%
7	1	10:17 AM	0.5		0%	6%	2%		0%	0%	0%		0%	0%	0%		1%	0%	0%
8	2	10:19 AM	0.5		6%	9%	1%		0%	0%	0%		0%	0%	0%		1%	0%	0%
9	1	11:07 AM	1		2%	4%	1%		-2%	0%	0%		3%	0%	0%		0%	0%	0%
10	1	12:22 PM	3		-1%	-1%	-1%		2%	-1%	0%		3%	1%	0%		2%	0%	0%
11	1	12:33 PM	1		-1%	1%	-11%		-3%	0%	0%		1%	0%	0%		1%	0%	0%
12	1	12:56 PM	2.5		1%	-1%	0%		0%	0%	0%		1%	0%	0%		1%	0%	0%
13	1	1:36 PM	1.5		2%	1%	-2%		-1%	0%	0%		1%	0%	-1%		0%	0%	0%
14	1	5:00 PM	0.5		-1%	4%	2%		0%	0%	0%		-1%	-2%	-2%		0%	0%	0%
15	1	6:21 PM	0.5		-2%	3%	3%		0%	0%	0%		-1%	0%	-1%		0%	0%	0%
16	1	9:09 PM	0.5		0%	5%	4%		0%	0%	0%		0%	-2%	-4%		0%	0%	0%
17	1	9:11 PM	1.5		0%	1%	-1%		0%	0%	0%		0%	0%	-1%		0%	0%	0%

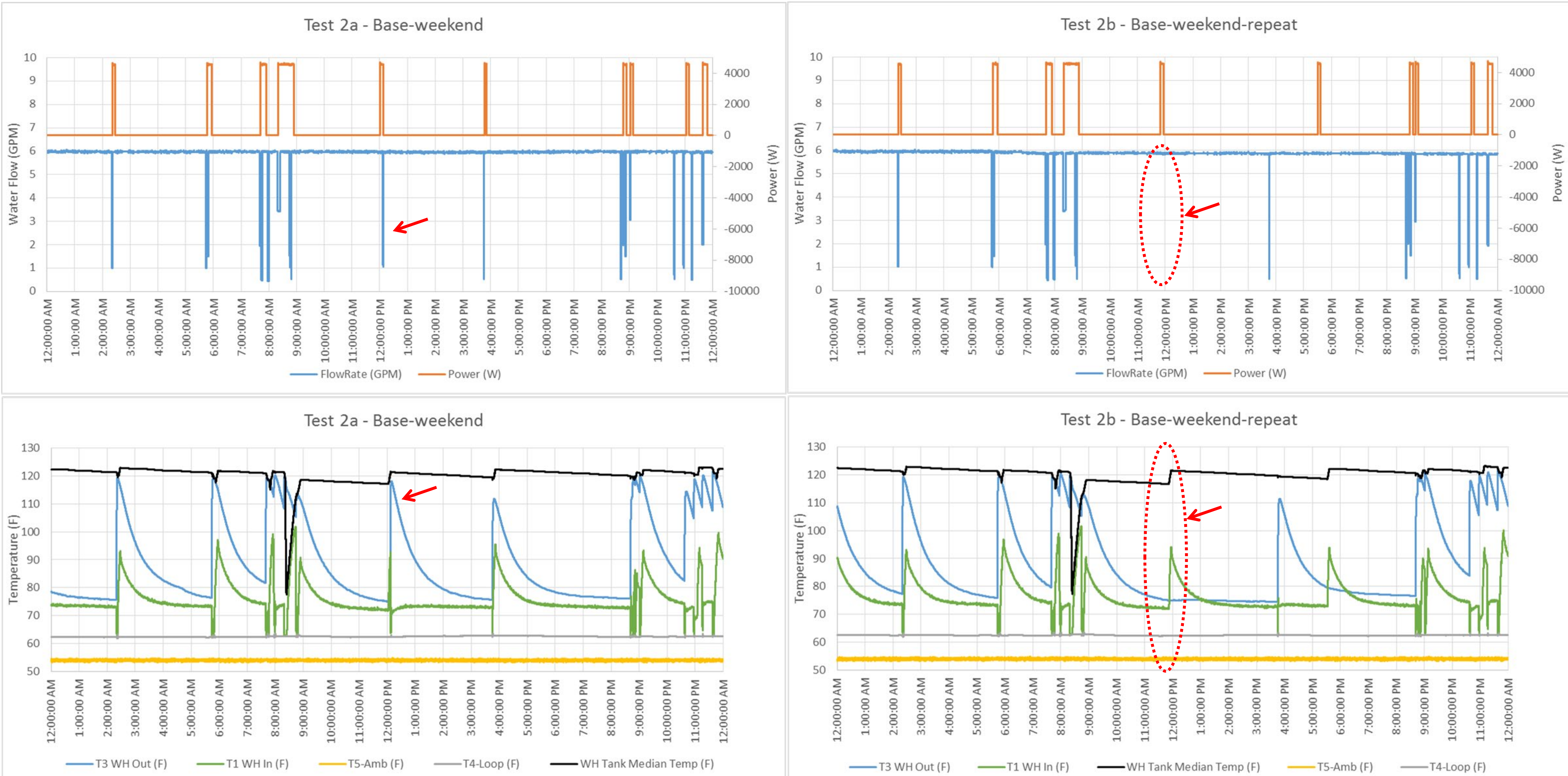
Observations: Figure 36 through Figure 38, and Table 10 (Tests 1b, 1c, and 3 vs benchmark Test 1a)

- For Tests 1b, 1c, and 3, the average water flow rate of every hot water draw event, (with benchmark Test 1a):
  - At flow rates of 1.5 gpm and above, the deviations were within 4%.
  - At flow rates of 0.5 gpm and 1.0 gpm, the deviations were within 11%.
  - Flow rates shown are mostly the flow of the recirculating water supply loop. Upon water draw events, water flow is routed completely through the water heater, where flow measurements reflect the draw flow rates.
- For Tests 1b, 1c, and 3, the T1 average inlet water temperatures of every hot water event, were within 3% (with benchmark Test 1a).
  - The T1 water heater inlet typically rises in conjunction with every heating event and falls with every hot water draw event. When neither a hot water draw nor heating event are present, T1 settles at a temperature elevated above the T4 loop temperature.
- For Tests 1b, 1c, and 3, the T3 average outlet water temperatures of every hot water event were mostly within 6% (with benchmark Test 1a).
  - For Test 1b, draw #1, deviation was 22% higher.
  - The T3 water heater outlet typically rises in conjunction with every hot water draw event to levels approaching the median tank temperature. T3 does not rise in response to heating events. When a hot water draw event is not present, T3 settles at a temperature elevated above the T4 loop temperature.
- For Tests 1b, 1c, and 3, the average median tank temperatures of the water heater of every hot water event were within 4% (with benchmark Test 1a).
- For Test 3, the RC Top Tank Temperature appears to be significantly lower than the median tank temperatures calculated. Every time there is a hot water draw event, the RC Top Tank Temp appears to increase/approach the median tank temperatures calculated with lab measurements.

Discussion: Figure 36 through Figure 38, and Table 10 (Tests 1b, 1c, and 3 vs benchmark Test 1a)

The water heater's power profile shape (number/timing of heating element events) was observed to have slight variances across Tests 1a – 3. This is likely attributable to slight variances and interactions of test parameters and the controls of the heating elements. The water heater is not a high-precision temperature control device, so the observed slight variances are not surprising and did not have major influences on the 24-hour metrics previously discussed. No major variances were observed with the activation of the retrofit controller in Test 3 under normal operating controls. The observed temperature responses of the water heater inlet and outlet appear to indicate that the inlet is susceptible to heating events. This is perhaps because it is connected to a long dip tube that extends to the bottom of the water heater, acting as a sort of heat exchanger/conductor.

Baseline Repeatability Testing: Weekend Profile



Note: Evidence of test 2b malfunction indicated for reference.

FIGURE 39. POWER, FLOW, AND TEMPERATURES - BASELINE WEEKEND TESTS 2A AND 2B

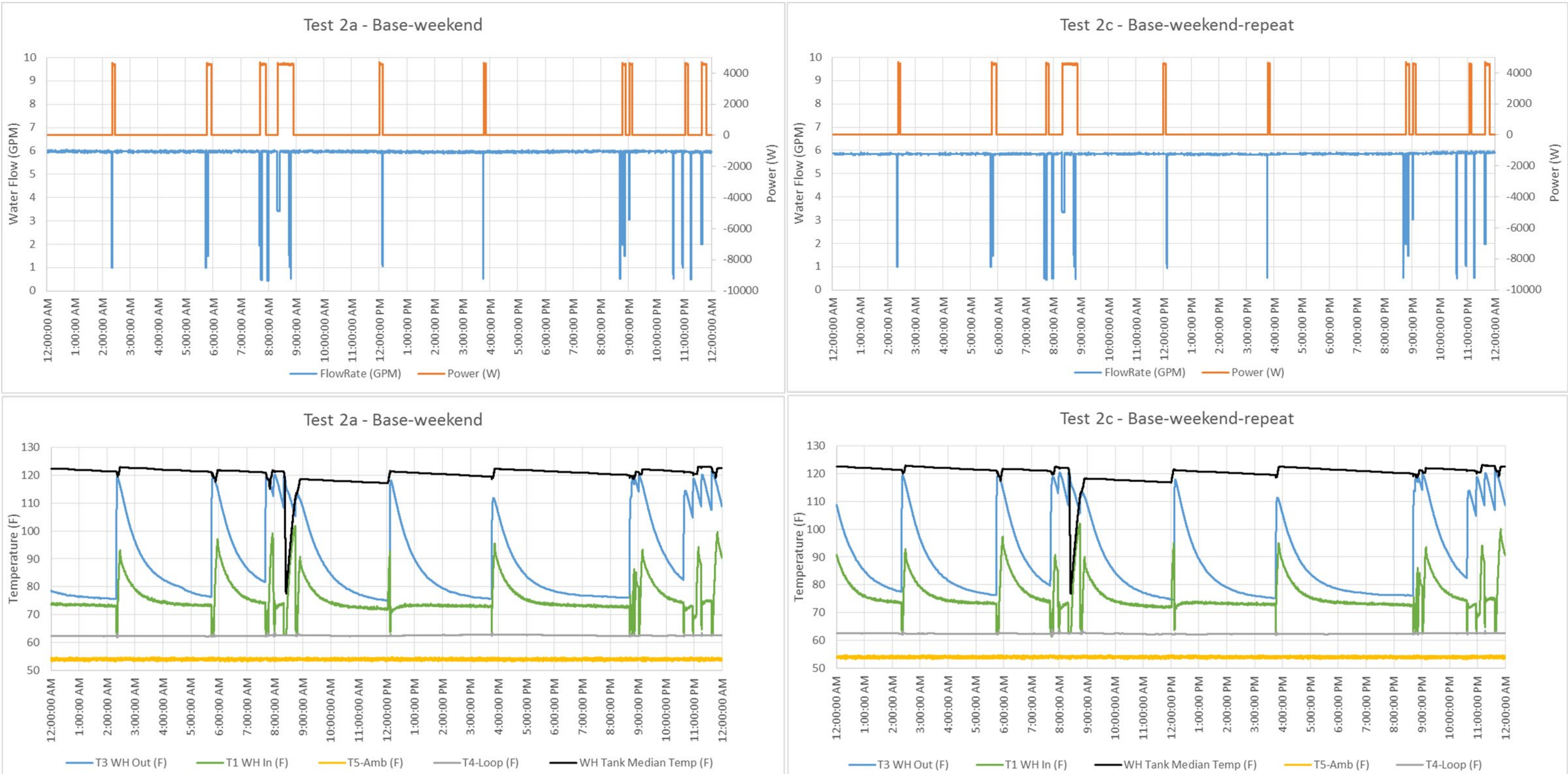


FIGURE 40. POWER, FLOW, AND TEMPERATURES - BASELINE WEEKEND TESTS 2A AND 2C

TABLE 11. BASELINE REPEATABILITY TEST DATA AND % DEVIATIONS FROM BENCHMARK – PER-HOT WATER DRAW EVENT ANALYSIS WINDOW ON TESTS 2A, 2B, AND 2C (WEEKEND PROFILE)

Sunday Draw Profile				2a	2b	2c	2a	2b	2c	2a	2b	2c	2a	2b	2c
Draw	Dur (min)	Time	Target GPM	FlowRate (GPM)			T1 WH In (F)			T3 WH Out (F)			WH Tank Median (F)		
1	2	2:20 AM	1	1.01	1.03	1.01	63.0	63.1	63.2	112.4	113.1	112.4	120.8	120.8	121.0
2	1	5:44 AM	1	1.01	1.03	1.01	63.9	63.9	63.9	104.5	107.5	105.2	120.9	121.1	121.0
3	3	5:46 AM	1.5	1.49	1.50	1.47	62.8	62.9	62.9	119.6	119.7	119.6	120.0	120.1	119.9
4	3	7:40 AM	2	1.95	1.96	0.51	63.1	63.1	62.7	117.1	117.1	100.8	120.1	120.0	120.6
5	1	7:43 AM	0.5	0.53	0.52	0.49	62.8	62.8	61.6	119.0	118.9	116.9	118.9	118.9	120.2
6	1	7:45 AM	0.5	0.48	0.47	0.47	64.4	64.4	64.1	118.5	118.5	118.8	118.6	118.5	120.1
7	1	7:57 AM	0.5	0.49	0.51	0.52	71.8	71.7	68.0	117.7	117.8	116.1	121.6	121.4	122.3
8	1	7:59 AM	0.5	0.46	0.48	0.50	65.7	65.5	64.9	120.1	120.1	120.1	121.5	121.3	122.1
9	5	8:19 AM	3.5	3.45	3.41	3.35	63.0	63.1	62.9	118.6	118.4	119.3	106.6	106.4	106.7
10	1	8:44 AM	1.5	1.52	1.49	1.49	70.3	70.5	70.9	111.1	111.0	111.5	112.5	112.3	112.5
11	1	8:46 AM	1	1.03	1.04	1.01	64.2	64.2	64.2	112.0	112.1	112.1	113.4	113.1	113.3
12	1	8:48 AM	0.5	0.53	0.53	0.50	64.4	64.3	64.3	113.0	112.6	112.7	114.1	113.9	114.0
13	1	12:07 PM	1	1.06	5.85	0.96	67.4	85.9	67.7	108.8	75.0	106.1	121.3	121.4	121.4
14	1	3:45 PM	0.5	0.57	0.57	0.55	63.9	63.8	63.7	90.0	81.7	82.0	119.4	119.5	119.3
15	1	8:41 PM	0.5	0.56	0.55	0.55	63.7	63.6	63.6	92.1	93.0	95.3	119.8	120.5	119.9
16	1	8:46 PM	2	2.00	1.98	1.97	64.1	64.0	63.9	117.9	118.7	118.1	119.4	120.2	119.5
17	1	8:51 PM	1.5	1.48	1.49	1.46	66.5	63.2	66.2	118.9	119.2	118.8	119.6	119.4	119.6
18	1	9:01 PM	3	3.05	3.00	3.02	64.8	65.6	64.9	119.4	119.8	119.3	121.0	121.3	120.9
19	1	10:37 PM	0.5	0.55	0.57	0.53	64.0	64.0	64.0	95.8	110.2	87.8	121.2	121.2	121.1
20	1	10:57 PM	1	1.02	1.00	1.02	64.1	64.1	64.1	115.2	117.3	115.1	120.8	120.9	120.8
21	1	11:15 PM	0.5	0.53	0.52	0.53	68.1	68.3	68.2	117.0	118.0	116.7	122.9	122.9	122.9
22	3	11:37 PM	2	1.99	1.96	1.97	63.3	63.3	63.3	120.8	120.9	120.5	122.0	121.9	121.9

Sunday Draw Profile				2a	2b	2c	2a	2b	2c	2a	2b	2c	2a	2b	2c
Draw	Dur (min)	Time	Target GPM	FlowRate (% Dev)			T1 WH In (% Dev)			T3 WH Out (% Dev)			WH Tank Median (% Dev)		
1	2	2:20 AM	1		3%	0%		0%	0%		1%	0%		0%	0%
2	1	5:44 AM	1		3%	1%		0%	0%		3%	1%		0%	0%
3	3	5:46 AM	1.5		0%	-1%		0%	0%		0%	0%		0%	0%
4	3	7:40 AM	2		1%	-74%		0%	-1%		0%	-14%		0%	0%
5	1	7:43 AM	0.5		-3%	-8%		0%	-2%		0%	-2%		0%	1%
6	1	7:45 AM	0.5		-2%	-2%		0%	-1%		0%	0%		0%	1%
7	1	7:57 AM	0.5		5%	6%		0%	-5%		0%	-1%		0%	1%
8	1	7:59 AM	0.5		5%	9%		0%	-1%		0%	0%		0%	0%
9	5	8:19 AM	3.5		-1%	-3%		0%	0%		0%	1%		0%	0%
10	1	8:44 AM	1.5		-2%	-2%		0%	1%		0%	0%		0%	0%
11	1	8:46 AM	1		1%	-2%		0%	0%		0%	0%		0%	0%
12	1	8:48 AM	0.5		-1%	-6%		0%	0%		0%	0%		0%	0%
13	1	12:07 PM	1		451%	-9%		28%	0%		-31%	-2%		0%	0%
14	1	3:45 PM	0.5		-1%	-4%		0%	0%		-9%	-9%		0%	0%
15	1	8:41 PM	0.5		-1%	-1%		0%	0%		1%	3%		1%	0%
16	1	8:46 PM	2		-1%	-1%		0%	0%		1%	0%		1%	0%
17	1	8:51 PM	1.5		0%	-2%		-5%	0%		0%	0%		0%	0%
18	1	9:01 PM	3		-1%	-1%		1%	0%		0%	0%		0%	0%
19	1	10:37 PM	0.5		4%	-3%		0%	0%		15%	-8%		0%	0%
20	1	10:57 PM	1		-1%	1%		0%	0%		2%	0%		0%	0%
21	1	11:15 PM	0.5		-2%	0%		0%	0%		1%	0%		0%	0%
22	3	11:37 PM	2		-1%	-1%		0%	0%		0%	0%		0%	0%

Observations: Figure 39, Figure 40, and Table 11 (Tests 2b and 2c vs benchmark Test 2a)

- For Test 2b, the average water flow rate of every hot water draw event, (with benchmark Test 2a) generally had deviations within 5%. However, draw event #13 did not occur in Test 2b due to test rig malfunction. (The recirculation loop flow is reported, no flow is occurring through the water heater.)
- For Test 2c, the average water flow rate of every hot water draw event, (with benchmark Test 2a) generally had deviations within 9%. However, draw event #4 resulted in a flow deviation of -74% due to test rig malfunction.
- For Tests 2b and 2c the deviations of T1 average inlet water temperatures of every hot water event, were within 5% (with benchmark Test 2a). However, draw #13 of Test 2b, resulted in a 28% deviation in T1 temperature due to test rig malfunction. (A heating event occurred coincidentally, but there was no water draw to displace water in the inlet section.)
- For Tests 2b and 2c, the T3 average outlet water temperatures of every hot water event, were mostly within 10% (with benchmark Test 2a). However, test rig malfunctions resulted in T3 temperature deviations of -31% for draw #13 in Test 2b, and -14% for draw #4 in Test 2c.
- For Tests 2b and 2c, the average median tank temperatures of the water heater of every hot water event, had deviations within 1% (with benchmark Test 1a).

Discussion: Figure 39, Figure 40, and Table 11 (Tests 2b and 2c vs benchmark Test 2a)

Both Tests 2b and 2c, each had test rig malfunctions that prevented one draw from occurring correctly from the 22 scheduled draws. Outside of these events there was reasonable repeatability observed in parameters measured/averaged over each hot water event. The power profile and median tank temperature profiles appear to be reasonably similar across Tests 2a – 2c.

Load Curtailment Testing: Weekday Profile

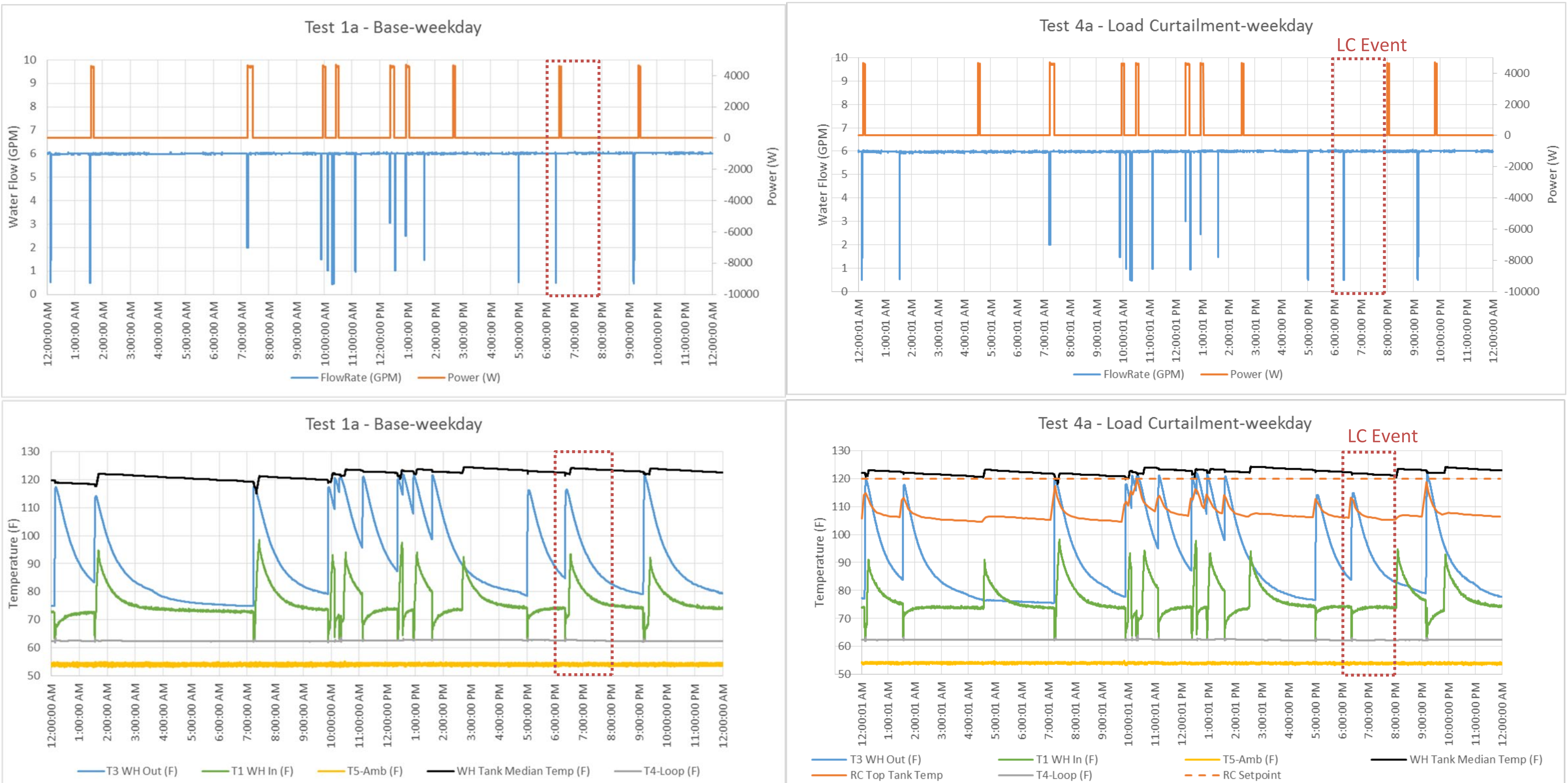


Figure 41. Power, Flow, and Temperatures – Comparing Baseline vs Load Curtailment Tests 1a AND 4A

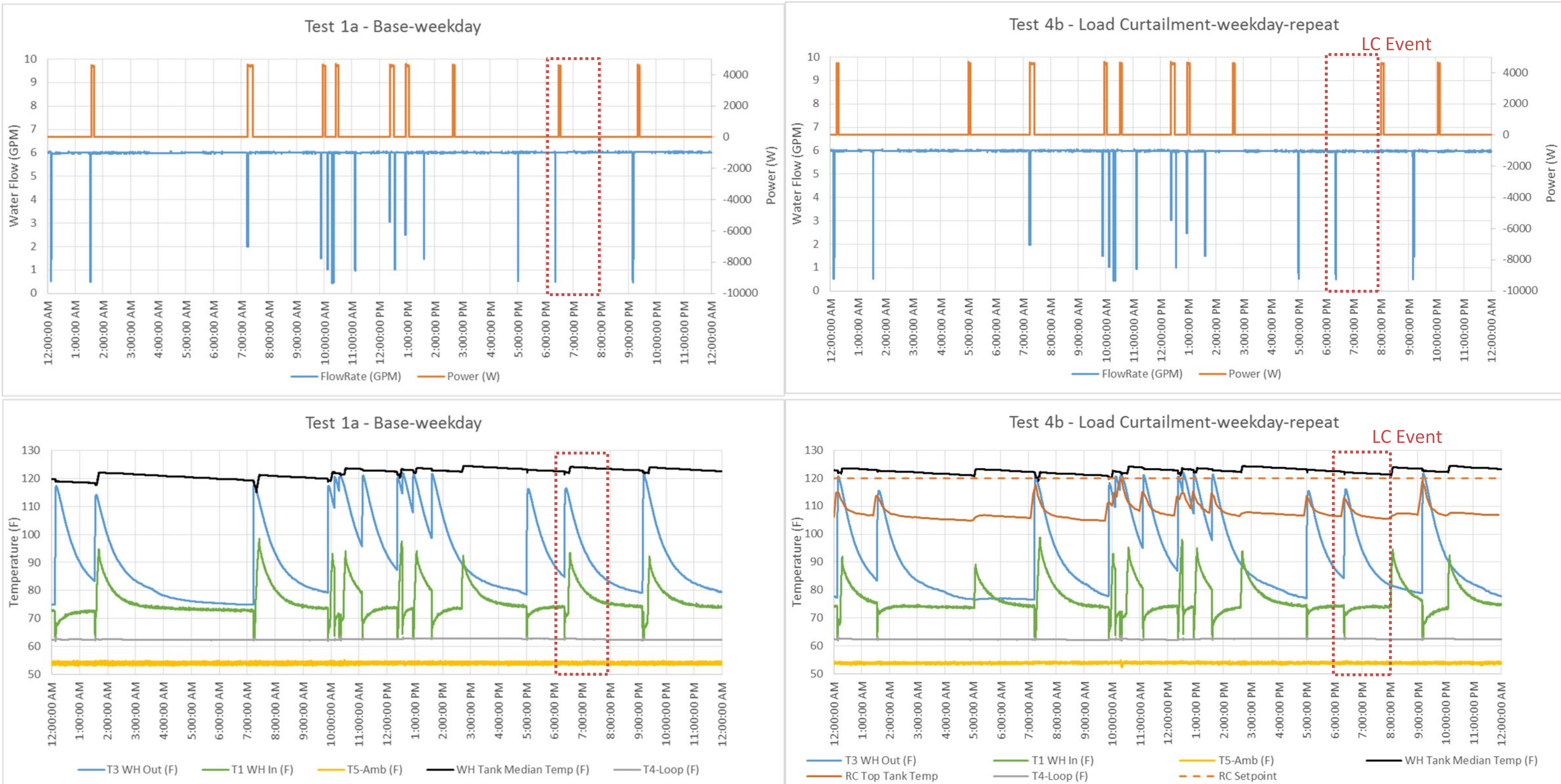


Figure 42. Power, Flow, And Temperatures – Comparing Baseline vs Load Curtailment Tests 1a and 4b

TABLE 12. LOAD CURTAILMENT TESTS – LC EVENT ANALYSIS WINDOW, TEST DATA AND % DEVIATIONS FROM BENCHMARK

Test	Time Period	Start Time	End Time	Energy (kWh)	Heater Runtime (min)	WH Tank Average Median Temp (F)	WH Tank Median Temp - Start (F)	WH Tank Median Temp - End (F)
1a	Load Curtailment	6:00 PM	8:00 PM	0.34	4.4	123.3	122.6	123.4
4a				0.01	0.0	121.6	122.4	121.1
4b				0.01	0.0	121.8	122.5	121.3

Test	Time Period	Start Time	End Time	Energy (% Dev)	Heater Runtime (% Dev)	WH Tank Average Median Temp (% Dev)	WH Tank Median Temp - Start (% Dev)	WH Tank Median Temp - End (% Dev)
1a	Load Curtailment	6:00 PM	8:00 PM					
4a				-98%	-100%	-1%	0%	-2%
4b				-98%	-100%	-1%	0%	-2%

TABLE 13. LOAD CURTAILMENT CONTROLS TEST DATA AND % DEVIATIONS FROM BENCHMARK – PER-HOT WATER DRAW EVENT ANALYSIS WINDOW (WEEKDAY PROFILE)

Monday Draw Profile				Avg Flow Rate (GPM)			T1 WH In Avg Temp (F)			T3 WH Out Avg Temp (F)			WH Tank Avg Median Temp (F)		
Draw	Dur (min)	Time	Target GPM	1a	4a	4b	1a	4a	4b	1a	4a	4b	1a	4a	4b
1	1	12:07 AM	0.5	0.55	0.55	0.58	63.8	64.2	64.1	88.1	90.2	91.8	119.6	121.9	122.7
2	1	12:08 AM	1.5	1.46	1.44	1.44	62.4	62.3	62.4	113.0	115.5	116.1	119.2	121.6	122.4
3	1	1:33 AM	0.5	0.54	0.58	0.56	63.6	64.5	64.4	105.2	106.8	94.6	118.3	122.2	122.8
4	3	7:13 AM	2	2.00	1.98	1.98	63.0	63.2	62.9	115.2	117.3	118.5	118.4	120.8	121.4
5	1	9:53 AM	1.5	1.51	1.47	1.50	63.9	64.0	64.1	110.2	110.3	109.0	119.7	120.6	120.5
6	1	10:07 AM	1	1.02	0.99	1.03	67.7	68.0	67.6	118.3	118.7	118.2	122.1	122.6	122.5
7	1	10:17 AM	0.5	0.48	0.53	0.49	64.3	64.3	64.4	119.1	119.5	119.2	121.8	122.1	122.2
8	2	10:19 AM	0.5	0.47	0.49	0.46	63.5	63.5	63.5	120.9	121.2	121.0	121.5	121.9	121.9
9	1	11:07 AM	1	0.99	0.98	0.95	65.2	65.8	65.5	115.8	115.6	115.0	123.2	123.6	123.6
10	1	12:22 PM	3	3.07	3.05	3.04	64.0	64.0	63.9	114.7	114.5	114.6	122.0	122.4	122.4
11	1	12:33 PM	1	1.03	0.94	1.01	69.7	69.9	69.6	120.5	120.3	120.6	123.2	123.4	123.3
12	1	12:56 PM	2.5	2.50	2.46	2.48	64.3	64.1	64.0	119.2	119.0	119.2	122.8	122.8	122.8
13	1	1:36 PM	1.5	1.47	1.47	1.50	65.8	65.5	65.7	117.4	115.7	117.0	123.3	122.9	123.1
14	1	5:00 PM	0.5	0.55	0.55	0.56	64.1	64.1	64.2	94.6	82.6	91.7	123.1	122.9	123.0
15	1	6:21 PM	0.5	0.54	0.55	0.54	64.1	64.0	64.1	99.2	96.0	98.3	122.3	122.1	122.2
16	1	9:09 PM	0.5	0.53	0.55	0.55	64.0	64.6	64.7	95.5	96.7	95.4	122.7	122.8	123.3
17	1	9:11 PM	1.5	1.47	1.50	1.47	64.1	64.3	64.3	120.2	120.7	120.7	122.4	122.6	123.0

Monday Draw Profile				Avg Flow Rate (% Dev)			T1 WH In Avg Temp (% Dev)			T3 WH Out Avg Temp (% Dev)			WH Tank Avg Median Temp (% Dev)		
Draw	Dur (min)	Time	Target GPM	1a	4a	4b	1a	4a	4b	1a	4a	4b	1a	4a	4b
1	1	12:07 AM	0.5		-1%	4%		1%	1%		2%	4%		2%	3%
2	1	12:08 AM	1.5		-1%	-1%		0%	0%		2%	3%		2%	3%
3	1	1:33 AM	0.5		8%	4%		1%	1%		2%	-10%		3%	4%
4	3	7:13 AM	2		-1%	-1%		0%	0%		2%	3%		2%	3%
5	1	9:53 AM	1.5		-3%	-1%		0%	0%		0%	-1%		1%	1%
6	1	10:07 AM	1		-3%	0%		0%	0%		0%	0%		0%	0%
7	1	10:17 AM	0.5		9%	2%		0%	0%		0%	0%		0%	0%
8	2	10:19 AM	0.5		3%	-2%		0%	0%		0%	0%		0%	0%
9	1	11:07 AM	1		0%	-4%		1%	0%		0%	-1%		0%	0%
10	1	12:22 PM	3		-1%	-1%		0%	0%		0%	0%		0%	0%
11	1	12:33 PM	1		-8%	-2%		0%	0%		0%	0%		0%	0%
12	1	12:56 PM	2.5		-2%	-1%		0%	0%		0%	0%		0%	0%
13	1	1:36 PM	1.5		0%	2%		0%	0%		-1%	0%		0%	0%
14	1	5:00 PM	0.5		0%	1%		0%	0%		-13%	-3%		0%	0%
15	1	6:21 PM	0.5		1%	1%		0%	0%		-3%	-1%		0%	0%
16	1	9:09 PM	0.5		4%	4%		1%	1%		1%	0%		0%	0%
17	1	9:11 PM	1.5		2%	0%		0%	0%		0%	0%		0%	0%

Observations: Figure 41, Figure 42, Table 12, and Table 13 (Tests 4a and 4b vs benchmark Test 1a)

Analysis window normalized to the load curtailment period from 6:00 PM – 8:00 PM.

- Energy and heater runtime were 0.
- Deviations of water heater average median temperatures were within 1%.
- Deviations of starting and ending median tank temperatures were within 2%.
- Median water heater tank temperature decreased 1.3°F and 1.2°F for Test 4a and Test 4b, respectively.

Analysis window normalized to every hot water draw event.

- For the average water flow rate of every hot water draw event, the deviations were within 9%.
    - Deviations were within 4%, for events with target flow rates above 0.5 gpm.
- For the T1 average inlet water temperatures of every hot water event, deviations were within 1%.
- For the T3 average outlet water temperatures of every hot water event, deviations were within 13%.
    - Deviations were within 3%, for events with target flow rates above 0.5 gpm.
- For the average median tank temperatures of the water heater, the deviations were within 4%.

Figure 41, Figure 42, Table 12, and Table 13 Discussion (Tests 4a and 4b vs benchmark Test 1a)

Load was successfully curtailed by the retrofit controller as expected. Water heater tank median starting and ending temperature drops were minimal during the load curtailment period. This is likely due to minimal water usage from 6:00 PM – 8:00 PM (draw #15 = 0.5 gpm, 1-min duration) and minimal standing losses. Tests 4a and 4b were reasonably repeatable.

TOU Controls Testing: Weekday Profile

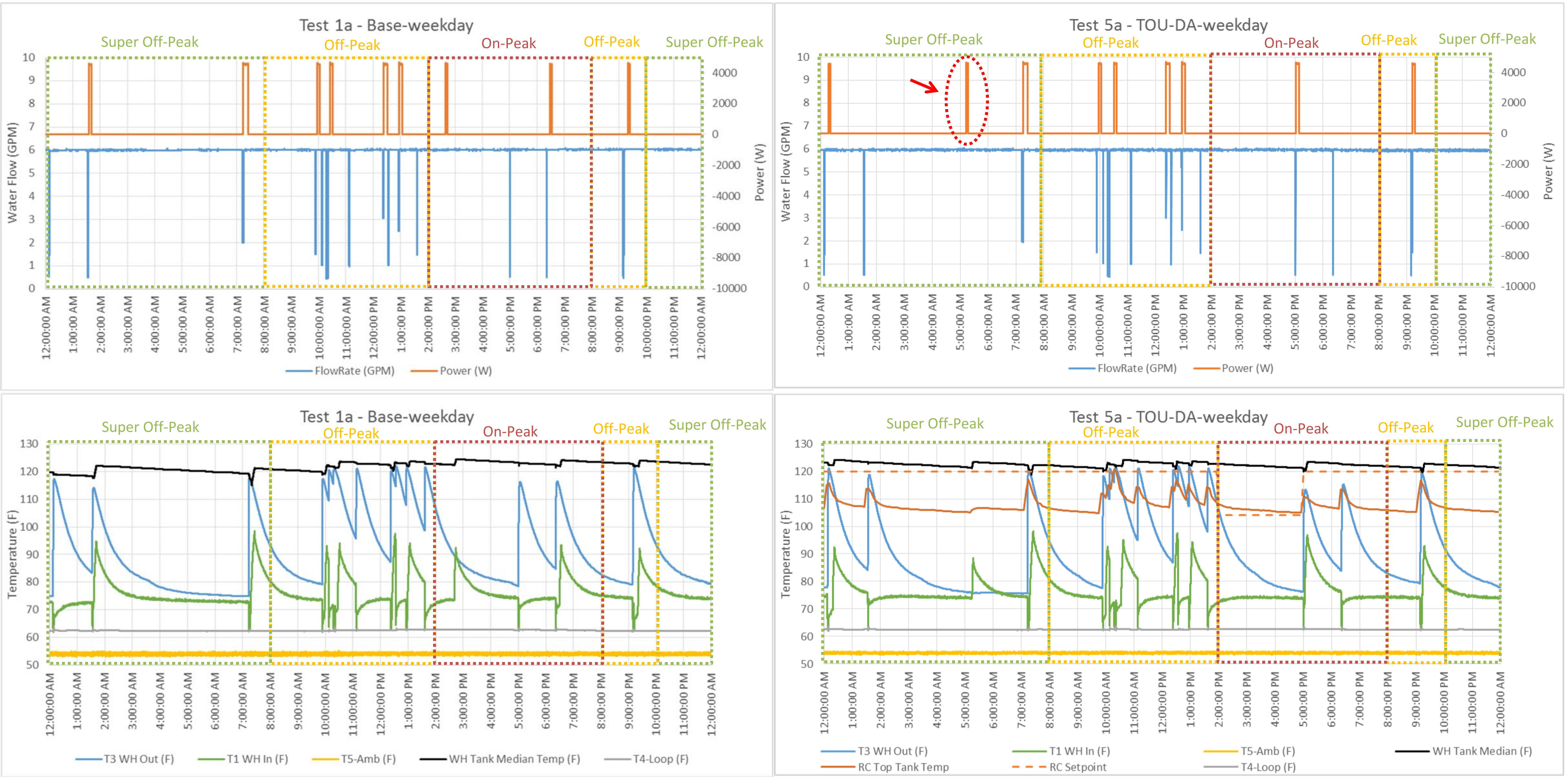


Figure 43. Power, Flow, and Temperatures – Comparing Baseline vs TOU Controls Tests 1a and 5a

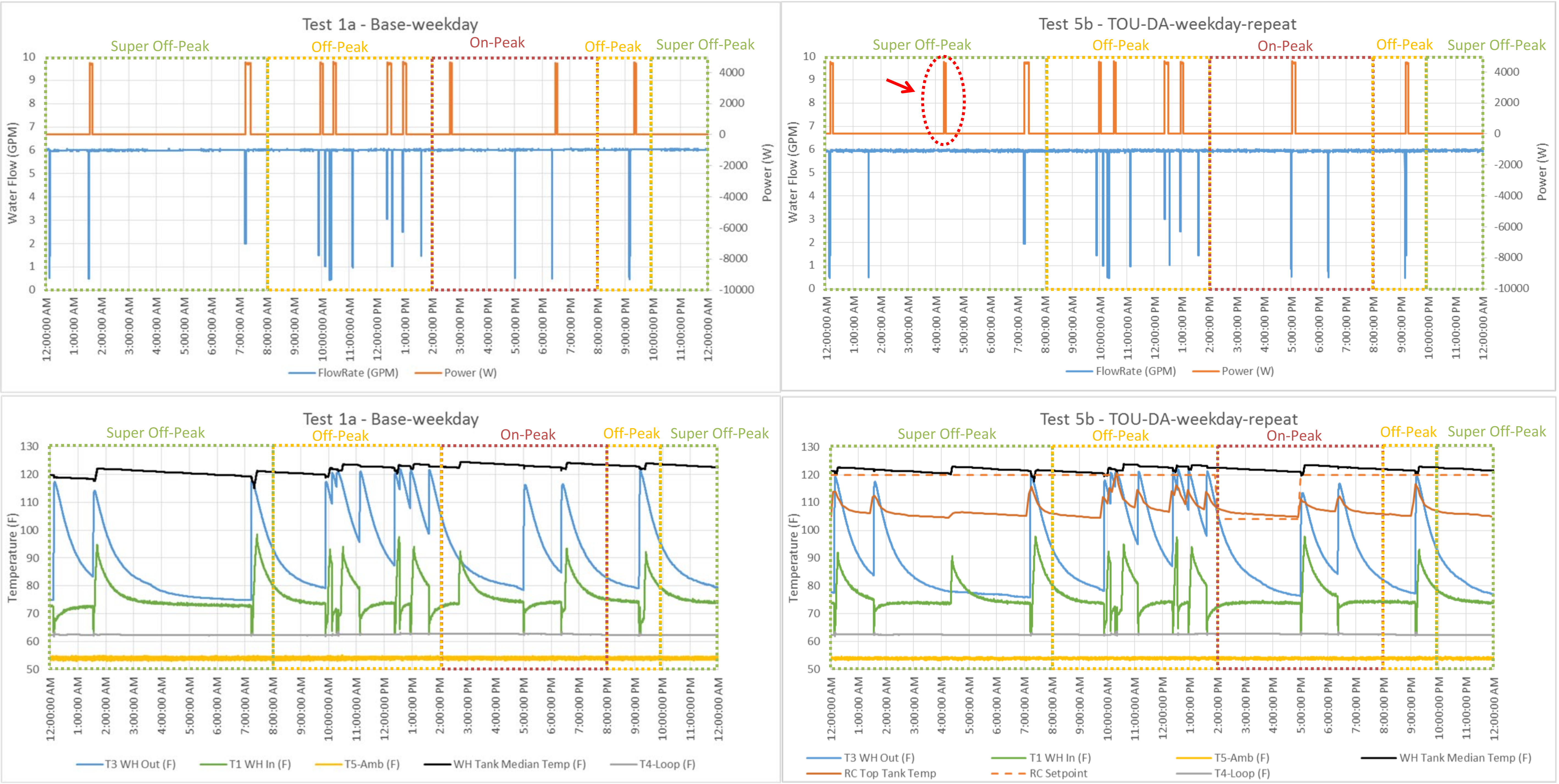


FIGURE 44. POWER, FLOW, AND TEMPERATURES – COMPARING BASELINE VS TOU CONTROLS TESTS 1A AND 5B

TABLE 14. WEEKDAY TOU CONTROLS TESTS – TOU PRICE WINDOWS, TEST DATA AND % DEVIATIONS FROM BENCHMARK

Test	Time Period	Start Time	End Time	Energy (kWh)	Heater Runtime (min)	WH Tank Average Median Temp	WH Tank Median Temp - Start (F)	WH Tank Median Temp - End (F)
1a	Super Off-Peak (TOU-DA-Weekday-Winter)	12:00 AM	8:00 AM	1.3	16.8	120.2	119.6	120.8
5a				1.4	18.1	122.7	123.2	122.2
5b				1.5	19.4	121.7	121.4	121.5
1a	Off-Peak (TOU-DA-Weekday-Winter)	8:00 AM	2:00 PM	2.0	25.8	121.9	120.8	122.7
5a				1.9	24.9	122.6	122.2	122.7
5b				1.9	25.2	122.2	121.5	122.5
1a	On-Peak (TOU-DA-Weekday-Winter)	2:00 PM	8:00 PM	0.7	8.9	123.3	122.7	123.4
5a				0.5	6.1	122.2	122.7	121.8
5b				0.5	6.4	122.2	122.5	122.0
1a	Off-Peak (TOU-DA-Weekday-Winter)	8:00 PM	10:00 PM	0.3	4.5	123.1	123.4	123.5
5a				0.4	5.8	121.9	121.8	122.5
5b				0.4	5.8	122.0	122.0	122.6
1a	Super Off-Peak (TOU-DA-Weekday-Winter)	10:00 PM	12:00 AM	0.0	0.0	123.0	123.5	122.5
5a				0.0	0.0	121.9	122.5	121.4
5b				0.0	0.0	122.0	122.6	121.5

Test	Time Period	Start Time	End Time	Energy (% Dev)	Heater Runtime (% Dev)	WH Tank Average Median Temp (% Dev)	WH Tank Median Temp - Start (% Dev)	WH Tank Median Temp - End (% Dev)
1a	Super Off-Peak (TOU-DA-Weekday-Winter)	12:00 AM	8:00 AM					
5a				8%	8%	2%	3%	1%
5b				15%	15%	1%	1%	1%
1a	Off-Peak (TOU-DA-Weekday-Winter)	8:00 AM	2:00 PM					
5a				-3%	-3%	1%	1%	0%
5b				-2%	-2%	0%	1%	0%
1a	On-Peak (TOU-DA-Weekday-Winter)	2:00 PM	8:00 PM					
5a				-30%	-31%	-1%	0%	-1%
5b				-27%	-28%	-1%	0%	-1%
1a	Off-Peak (TOU-DA-Weekday-Winter)	8:00 PM	10:00 PM					
5a				28%	28%	-1%	-1%	-1%
5b				27%	27%	-1%	-1%	-1%
1a	Super Off-Peak (TOU-DA-Weekday-Winter)	10:00 PM	12:00 AM					
5a				-4%	-	-1%	-1%	-1%
5b				-3%	-	-1%	-1%	-1%

TABLE 15. TOU CONTROLS TEST DATA AND % DEVIATIONS FROM BENCHMARK – PER-HOT WATER DRAW EVENT ANALYSIS WINDOW (WEEKDAY PROFILE)

Monday Draw Profile				1a	5a	5b	1a	5a	5b	1a	5a	5b	1a	5a	5b
Draw	Dur (min)	Time	Target GPM	Avg Flow Rate (GPM)			T1 WH In Avg Temp (F)			T3 WH Out Avg Temp (F)			WH Tank Avg Median Temp (F)		
1	1	12:07 AM	0.5	0.55	0.57	0.56	63.8	64.3	64.1	88.1	83.5	92.3	119.6	122.9	121.3
2	1	12:08 AM	1.5	1.46	1.46	1.44	62.4	62.4	62.5	113.0	115.2	115.5	119.2	122.8	121.0
3	1	1:33 AM	0.5	0.54	0.57	0.55	63.6	64.6	64.5	105.2	108.3	107.5	118.3	123.3	122.0
4	3	7:13 AM	2	2.00	1.96	1.93	63.0	63.2	63.1	115.2	118.1	117.4	118.4	121.6	120.6
5	1	9:53 AM	1.5	1.51	1.49	1.45	63.9	64.2	64.1	110.2	109.8	109.7	119.7	121.0	120.3
6	1	10:07 AM	1	1.02	1.01	1.00	67.7	67.9	67.8	118.3	118.8	118.4	122.1	122.8	122.4
7	1	10:17 AM	0.5	0.48	0.51	0.53	64.3	64.6	64.5	119.1	119.6	119.3	121.8	122.4	122.0
8	2	10:19 AM	0.5	0.47	0.46	0.50	63.5	63.6	63.5	120.9	121.3	121.1	121.5	122.2	121.7
9	1	11:07 AM	1	0.99	0.99	0.99	65.2	65.9	65.9	115.8	115.7	115.2	123.2	123.8	123.4
10	1	12:22 PM	3	3.07	3.01	3.01	64.0	63.8	64.0	114.7	114.9	114.5	122.0	122.6	122.2
11	1	12:33 PM	1	1.03	0.99	1.02	69.7	69.7	69.8	120.5	120.6	120.5	123.2	123.4	123.2
12	1	12:56 PM	2.5	2.50	2.46	2.47	64.3	64.2	64.3	119.2	119.3	119.1	122.8	122.8	122.6
13	1	1:36 PM	1.5	1.47	1.46	1.46	65.8	65.6	65.9	117.4	116.4	116.5	123.3	123.2	123.1
14	1	5:00 PM	0.5	0.55	0.56	0.56	64.1	64.1	64.2	94.6	90.9	91.4	123.1	121.0	120.8
15	1	6:21 PM	0.5	0.54	0.56	0.54	64.1	64.5	64.8	99.2	94.4	98.9	122.3	122.7	122.8
16	1	9:09 PM	0.5	0.53	0.54	0.52	64.0	64.1	64.0	95.5	95.0	92.0	122.7	121.2	121.3
17	1	9:11 PM	1.5	1.47	1.50	1.44	64.1	64.1	64.1	120.2	119.0	118.1	122.4	120.9	121.0

Monday Draw Profile				1a	5a	5b	1a	5a	5b	1a	5a	5b	1a	5a	5b
Draw	Dur (min)	Time	Target GPM	Avg Flow Rate (% Dev)			T1 WH In Avg Temp (% Dev)			T3 WH Out Avg Temp (% Dev)			WH Tank Avg Median Temp (% Dev)		
1	1	12:07 AM	0.5		2%	1%		1%	1%		-5%	5%		3%	1%
2	1	12:08 AM	1.5		0%	-1%		0%	0%		2%	2%		3%	1%
3	1	1:33 AM	0.5		5%	1%		2%	1%		3%	2%		4%	3%
4	3	7:13 AM	2		-2%	-3%		0%	0%		3%	2%		3%	2%
5	1	9:53 AM	1.5		-1%	-3%		0%	0%		0%	-1%		1%	1%
6	1	10:07 AM	1		-1%	-3%		0%	0%		0%	0%		1%	0%
7	1	10:17 AM	0.5		7%	10%		0%	0%		0%	0%		1%	0%
8	2	10:19 AM	0.5		-2%	5%		0%	0%		0%	0%		1%	0%
9	1	11:07 AM	1		1%	0%		1%	1%		0%	-1%		0%	0%
10	1	12:22 PM	3		-2%	-2%		0%	0%		0%	0%		0%	0%
11	1	12:33 PM	1		-4%	-1%		0%	0%		0%	0%		0%	0%
12	1	12:56 PM	2.5		-2%	-1%		0%	0%		0%	0%		0%	0%
13	1	1:36 PM	1.5		-1%	-1%		0%	0%		-1%	-1%		0%	0%
14	1	5:00 PM	0.5		1%	1%		0%	0%		-4%	-3%		-2%	-2%
15	1	6:21 PM	0.5		3%	1%		1%	1%		-5%	0%		0%	0%
16	1	9:09 PM	0.5		2%	-1%		0%	0%		0%	-4%		-1%	-1%
17	1	9:11 PM	1.5		2%	-2%		0%	0%		-1%	-2%		-1%	-1%

Observations: Figure 43, Figure 44, Table 14 and Table 15 (Tests 5a and 5b vs benchmark Test 1a)

Analysis window normalized to each TOU period.

- During the TOU-DA-Weekday-Winter Super Off-Peak period (12:00 AM – 8:00 AM):
    - Energy and heater runtimes increased with deviations of 8% and 15% for Test 5a and Test 5b, respectively.
    - Average, starting and ending median tank temperatures saw deviations within 3%.
- During the TOU-DA-Weekday-Winter Off-Peak period (8:00 AM – 2:00 PM):
    - Energy and heater runtimes decreased with deviations of -3% and -2% for Test 5a and Test 5b, respectively.
    - Average, starting and ending median tank temperatures saw deviations within 1%.
- During the TOU-DA-Weekday-Winter On-Peak period (2:00 PM – 8:00 PM):
    - Energy usage decreased with deviations of -30% and -27% for Test 5a and Test 5b, respectively.
    - Heater runtimes decreased with deviations of -31% and -28% for Test 5a and Test 5b, respectively.
    - Average, starting and ending median tank temperatures saw deviations within 1%.
- During the TOU-DA-Weekday-Winter Off-Peak period (8:00 PM – 10:00 PM):
    - Energy and heater runtimes increased with deviations of 28% and 27% for Test 5a and Test 5b, respectively.
    - Average, starting and ending median tank temperatures saw deviations within 1%.
- During the TOU-DA-Weekday-Winter Super Off-Peak period (10:00 PM – 12:00 AM):
    - Energy usage and heating runtimes remained at roughly zero.
    - Average, starting and ending median tank temperatures saw deviations within 1%.

Analysis window normalized to every hot water draw event:

- For the average water flow rates, the deviations were within 10%:
    - Deviations were within 4%, for events with target flow rates above 0.5 gpm.
- For the T1 average inlet water temperatures, deviations were within 2%.
- For the T3 average outlet water temperatures, deviations were within 5%.
- For the average median tank temperatures, deviations were within 4%.

Discussion: Figure 43, Figure 44, Table 14 and Table 15 (Tests 5a and 5b vs benchmark Test 1a)

Water heating element runtimes and energy consumption were successfully decreased from the On-Peak period to Off-Peak periods using TOU controls under the selected weekday usage profile. Energy consumption and heating element runtimes decreased during the On-Peak period (2:00 PM – 8:00 PM) and increased during the Super Off-Peak (12:00 AM – 8:00 AM) and the second On-Peak period (8:00 PM – 10:00 PM). No appreciable impacts were observed to tank temperatures or delivered hot water.

It is likely that the water heater's mechanical thermostat limited the amount of energy

TOU Controls Testing: Weekend Profile

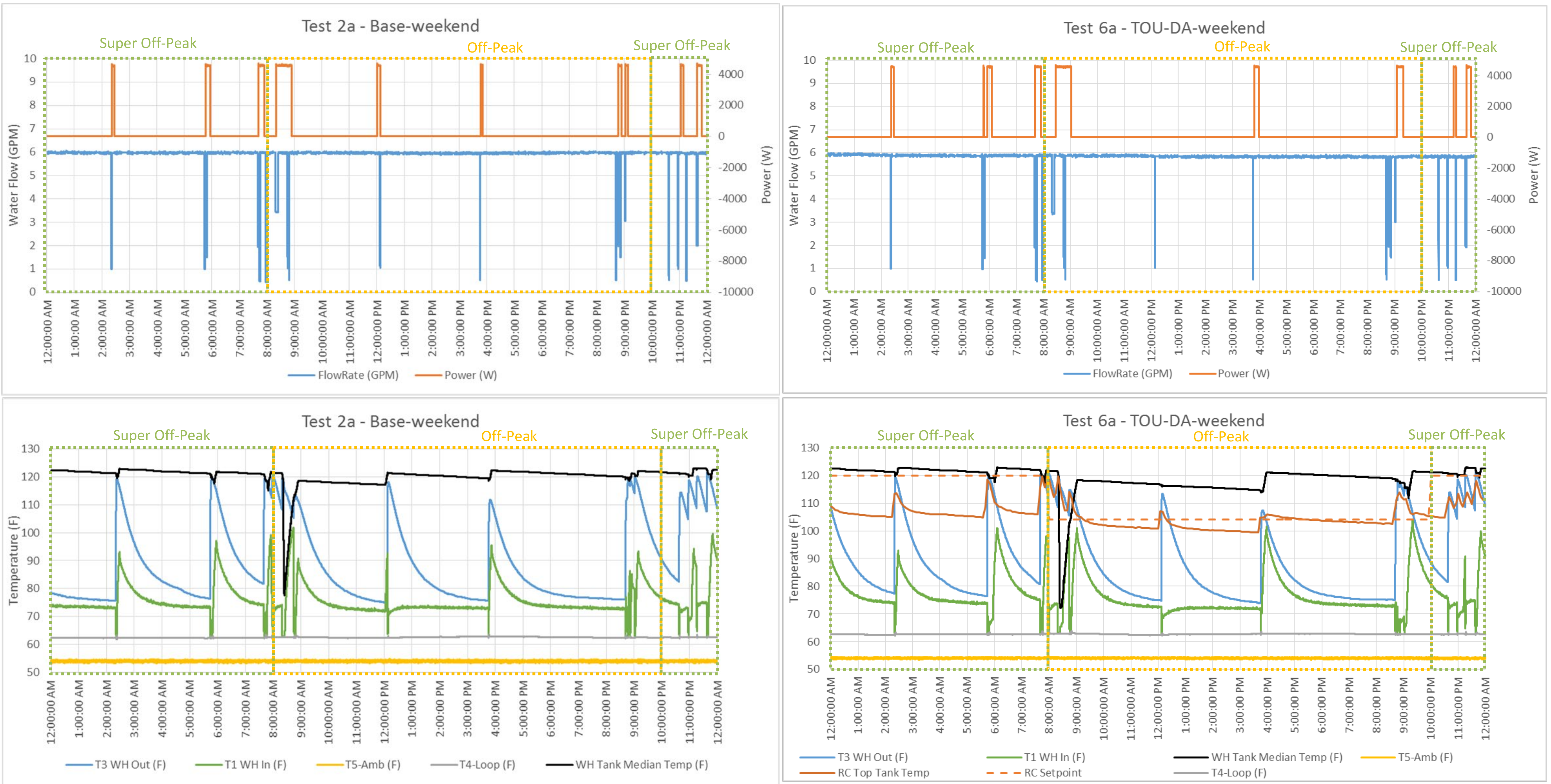


Figure 45. Power, Flow, and Temperatures – Comparing Baseline vs TOU Controls Tests 2a and 6a

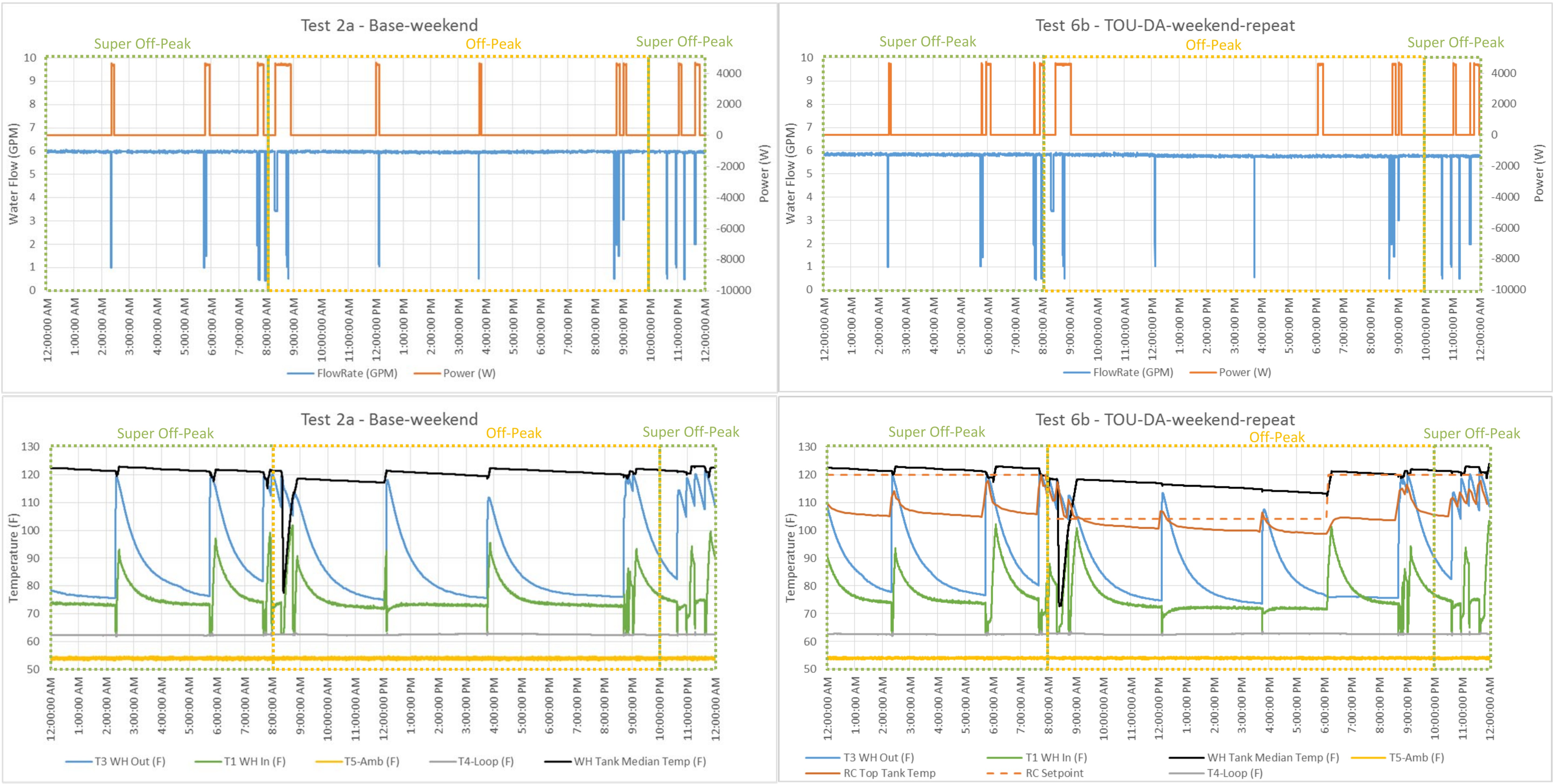


FIGURE 46. POWER, FLOW, AND TEMPERATURES – COMPARING BASELINE VS TOU CONTROLS TESTS 2A AND 6B

TABLE 16. WEEKEND TOU CONTROLS TESTS – TOU PRICE WINDOWS, TEST DATA AND % DEVIATIONS FROM BENCHMARK

Test	Time Period	Start Time	End Time	Energy (kWh)	Heater Runtime (min)	WH Tank Average Median Temp (F)	WH Tank Median Temp - Start (F)	WH Tank Median Temp - End (F)
2a	Super Off-Peak (TOU-DA-Weekend-Winter)	12:00 AM	8:00 AM	2.16	28.2	121.6	122.4	121.2
6a				2.19	28.4	121.8	122.4	121.6
6b				1.84	23.8	121.9	122.5	115.6
2a	Off-Peak (TOU-DA-Weekend-Winter)	8:00 AM	10:00 PM	4.59	59.9	119.4	121.3	121.6
6a				4.47	58.0	117.1	121.6	121.2
6b				4.78	62.2	116.2	115.4	121.5
2a	Super Off-Peak (TOU-DA-Weekend-Winter)	10:00 PM	12:00 AM	1.20	15.6	121.7	121.6	122.4
6a				1.20	15.8	121.3	121.2	122.5
6b				1.30	17.0	121.6	121.5	123.6

Test	Time Period	Start Time	End Time	Energy (% Dev)	Heater Runtime (% Dev)	WH Tank Average Median Temp (% Dev)	WH Tank Median Temp - Start (% Dev)	WH Tank Median Temp - End (% Dev)
2a	Super Off-Peak (TOU-DA-Weekend-Winter)	12:00 AM	8:00 AM					
6a				1%	1%	0%	0%	0%
6b				-15%	-16%	0%	0%	-5%
2a	Off-Peak (TOU-DA-Weekend-Winter)	8:00 AM	10:00 PM					
6a				-3%	-3%	-2%	0%	0%
6b				4%	4%	-3%	-5%	0%
2a	Super Off-Peak (TOU-DA-Weekend-Winter)	10:00 PM	12:00 AM					
6a				1%	1%	0%	0%	0%
6b				9%	9%	0%	0%	1%

TABLE 17. TOU CONTROLS TEST DATA – PER-HOT WATER DRAW EVENT ANALYSIS WINDOW (WEEKEND PROFILE)

Sunday Draw Profile				2a	6a	6b	2a	6a	6b	2a	6a	6b	2a	6a	6b
Draw	Dur (min)	Time	Target GPM	Avg Flow Rate (GPM)			T1 WH In Avg Temp (F)			T3 WH Out Avg Temp (F)			WH Tank Avg Median Temp (F)		
1	2	2:20 AM	1	1.01	1.00	1.00	63.0	63.2	63.2	112.4	112.7	113.3	120.8	120.9	121.2
2	1	5:44 AM	1	1.01	0.99	1.03	63.9	64.2	64.0	104.5	104.8	105.4	120.9	120.9	121.1
3	3	5:46 AM	1.5	1.49	1.44	1.43	62.8	63.0	62.9	119.6	119.5	119.8	120.0	120.0	120.3
4	3	7:40 AM	2	1.95	1.90	1.94	63.1	63.2	63.2	117.1	118.4	118.2	120.1	121.3	121.7
5	1	7:43 AM	0.5	0.53	0.50	0.51	62.8	62.9	62.9	119.0	120.2	120.3	118.9	120.3	120.6
6	1	7:45 AM	0.5	0.48	0.46	0.48	64.4	64.6	64.1	118.5	119.7	119.8	118.6	119.9	120.2
7	1	7:57 AM	0.5	0.49	0.51	0.53	71.8	71.5	66.0	117.7	118.4	117.6	121.6	121.8	119.8
8	1	7:59 AM	0.5	0.46	0.50	0.51	65.7	65.4	64.8	120.1	120.6	119.1	121.5	121.7	118.7
9	5	8:19 AM	3.5	3.45	3.37	3.39	63.0	63.2	63.3	118.6	118.8	116.5	106.6	105.6	110.0
10	1	8:44 AM	1.5	1.52	1.50	1.50	70.3	69.7	69.2	111.1	113.2	111.0	112.5	102.7	106.0
11	1	8:46 AM	1	1.03	1.02	1.02	64.2	64.3	64.0	112.0	114.8	112.4	113.4	103.9	106.3
12	1	8:48 AM	0.5	0.53	0.53	0.50	64.4	64.3	64.2	113.0	114.3	111.9	114.1	105.4	106.9
13	1	12:07 PM	1	1.06	1.03	1.02	67.4	63.9	63.7	108.8	102.9	100.8	121.3	116.6	116.8
14	1	3:45 PM	0.5	0.57	0.58	0.58	63.9	63.6	63.7	90.0	87.4	86.3	119.4	114.5	114.8
15	1	8:41 PM	0.5	0.56	0.55	0.53	63.7	63.8	64.0	92.1	90.4	82.3	119.8	118.8	120.0
16	1	8:46 PM	2	2.00	1.95	1.97	64.1	64.1	64.1	117.9	116.6	117.5	119.4	118.4	119.8
17	1	8:51 PM	1.5	1.48	1.47	1.44	66.5	63.4	65.4	118.9	117.2	118.2	119.6	117.8	119.5
18	1	9:01 PM	3	3.05	3.01	2.99	64.8	63.4	65.4	119.4	116.2	119.3	121.0	116.8	121.1
19	1	10:37 PM	0.5	0.55	0.54	0.53	64.0	64.5	64.0	95.8	94.7	87.4	121.2	120.8	121.2
20	1	10:57 PM	1	1.02	1.02	1.00	64.1	64.4	64.2	115.2	114.7	114.7	120.8	120.4	121.0
21	1	11:15 PM	0.5	0.53	0.54	0.52	68.1	68.8	68.3	117.0	116.5	116.7	122.9	122.3	122.8
22	3	11:37 PM	2	1.99	1.92	1.97	63.3	63.4	63.4	120.8	120.8	120.5	122.0	122.0	122.2

Sunday Draw Profile				2a	6a	6b	2a	6a	6b	2a	6a	6b	2a	6a	6b
Draw	Dur (min)	Time	Target GPM	Avg Flow Rate (% Dev)			T1 WH In Avg Temp (% Dev)			T3 WH Out Avg Temp (% Dev)			WH Tank Avg Median Temp (% Dev)		
1	2	2:20 AM	1		-1%	-1%		0%	0%		0%	1%		0%	0%
2	1	5:44 AM	1		-1%	2%		1%	0%		0%	1%		0%	0%
3	3	5:46 AM	1.5		-4%	-5%		0%	0%		0%	0%		0%	0%
4	3	7:40 AM	2		-3%	-1%		0%	0%		1%	1%		1%	1%
5	1	7:43 AM	0.5		-6%	-4%		0%	0%		1%	1%		1%	1%
6	1	7:45 AM	0.5		-4%	0%		0%	0%		1%	1%		1%	1%
7	1	7:57 AM	0.5		5%	7%		0%	-8%		1%	0%		0%	-1%
8	1	7:59 AM	0.5		9%	10%		-1%	-1%		0%	-1%		0%	-2%
9	5	8:19 AM	3.5		-2%	-2%		0%	1%		0%	-2%		-1%	3%
10	1	8:44 AM	1.5		-2%	-1%		-1%	-2%		2%	0%		-9%	-6%
11	1	8:46 AM	1		-1%	-1%		0%	0%		3%	0%		-8%	-6%
12	1	8:48 AM	0.5		0%	-5%		0%	0%		1%	-1%		-8%	-6%
13	1	12:07 PM	1		-3%	-4%		-5%	-5%		-5%	-7%		-4%	-4%
14	1	3:45 PM	0.5		1%	3%		0%	0%		-3%	-4%		-4%	-4%
15	1	8:41 PM	0.5		-1%	-4%		0%	1%		-2%	-11%		-1%	0%
16	1	8:46 PM	2		-2%	-2%		0%	0%		-1%	0%		-1%	0%
17	1	8:51 PM	1.5		-1%	-3%		-5%	-2%		-1%	-1%		-2%	0%
18	1	9:01 PM	3		-1%	-2%		-2%	1%		-3%	0%		-3%	0%
19	1	10:37 PM	0.5		-1%	-3%		1%	0%		-1%	-9%		0%	0%
20	1	10:57 PM	1		0%	-1%		1%	0%		0%	0%		0%	0%
21	1	11:15 PM	0.5		2%	0%		1%	0%		0%	0%		0%	0%
22	3	11:37 PM	2		-3%	-1%		0%	0%		0%	0%		0%	0%

Observations: Figure 45, Figure 46, Table 16, and Table 17 (Tests 6a and 6b vs benchmark Test 2a)

Analysis window normalized to each TOU period.

- During the TOU-DA-Weekend-Winter Super Off-Peak period (12:00 AM – 8:00 AM):
    - 1% deviations in energy consumption and heater runtimes for Test 6a.
    - -15% and -16% deviations in energy consumption and heater runtimes, respectively, for Test 6b.
    - Average, starting and ending median tank temperatures saw deviations within 5% for Test 6a and 6b. (Mostly negligible deviations, median tank temperature at the end of the Super Off-Peak for Test 6b saw -5% deviation.)
- During the TOU-DA-Weekend-Winter Off-Peak period (8:00 AM – 10:00 PM):
    - -3% deviations in energy consumption and heater runtimes for Test 6a.
    - 4% deviations in energy consumption and heater runtimes for Test 6b.
    - Average, starting and ending median tank temperatures saw deviations within 5%.
- During the TOU-DA-Weekend-Winter Super Off-Peak period (10:00 PM – 12:00 AM)
    - 1% deviations in energy consumption and heater runtimes for Test 6a.
    - 9% deviations in energy consumption and heater runtimes for Test 6b.
    - Average starting and ending median tank temperatures saw deviations within 1%.

Analysis window normalized to every hot water draw event.

- For the average water flow rates, the deviations were within 10%.
    - Deviations were within 5% for events with target flow rates above 0.5 gpm.
- For the T1 average inlet water temperatures deviations were within 8%.
- For the T3 average outlet water temperatures deviations were within 11%.
- For the average median tank temperatures deviations were within 9%.

Discussion: Figure 45, Figure 46, Table 16, and Table 17 (Tests 6a and 6b vs benchmark Test 2a)

Using TOU controls under the selected weekend usage profile yielded mixed results. In Test 6a, no appreciable impacts were observed to energy consumption/operation. In Test 6b, usage in the first Super Off-Peak period was unexpectedly mildly reduced, and usage was mildly increased during the proceeding Off-Peak and second Super Off Peak periods.

GIWH Controls Testing: Weekend Profile

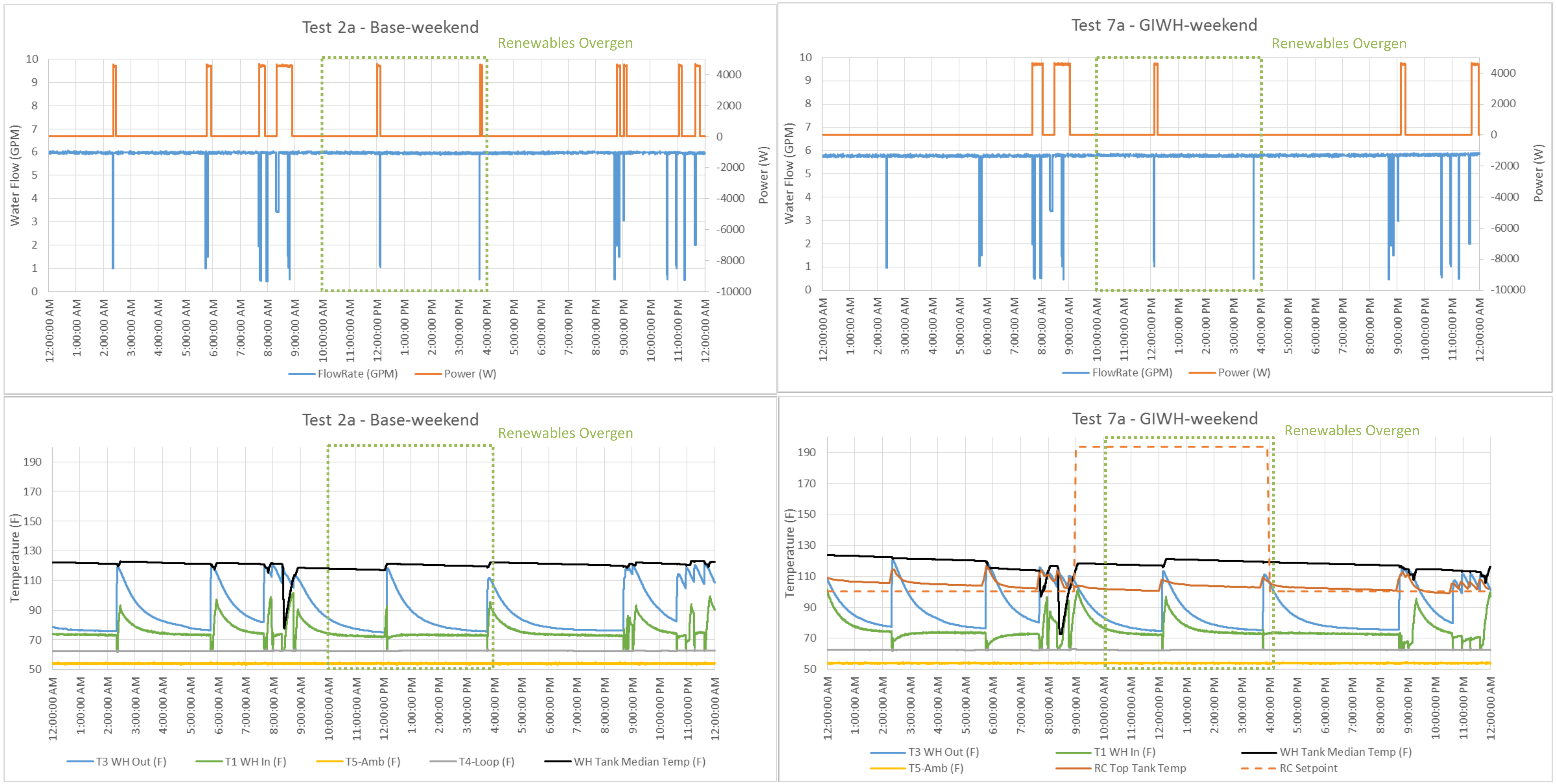


Figure 47. Power, Flow, and Temperatures – Comparing Baseline vs GIWH Controls Tests 2a and 7a

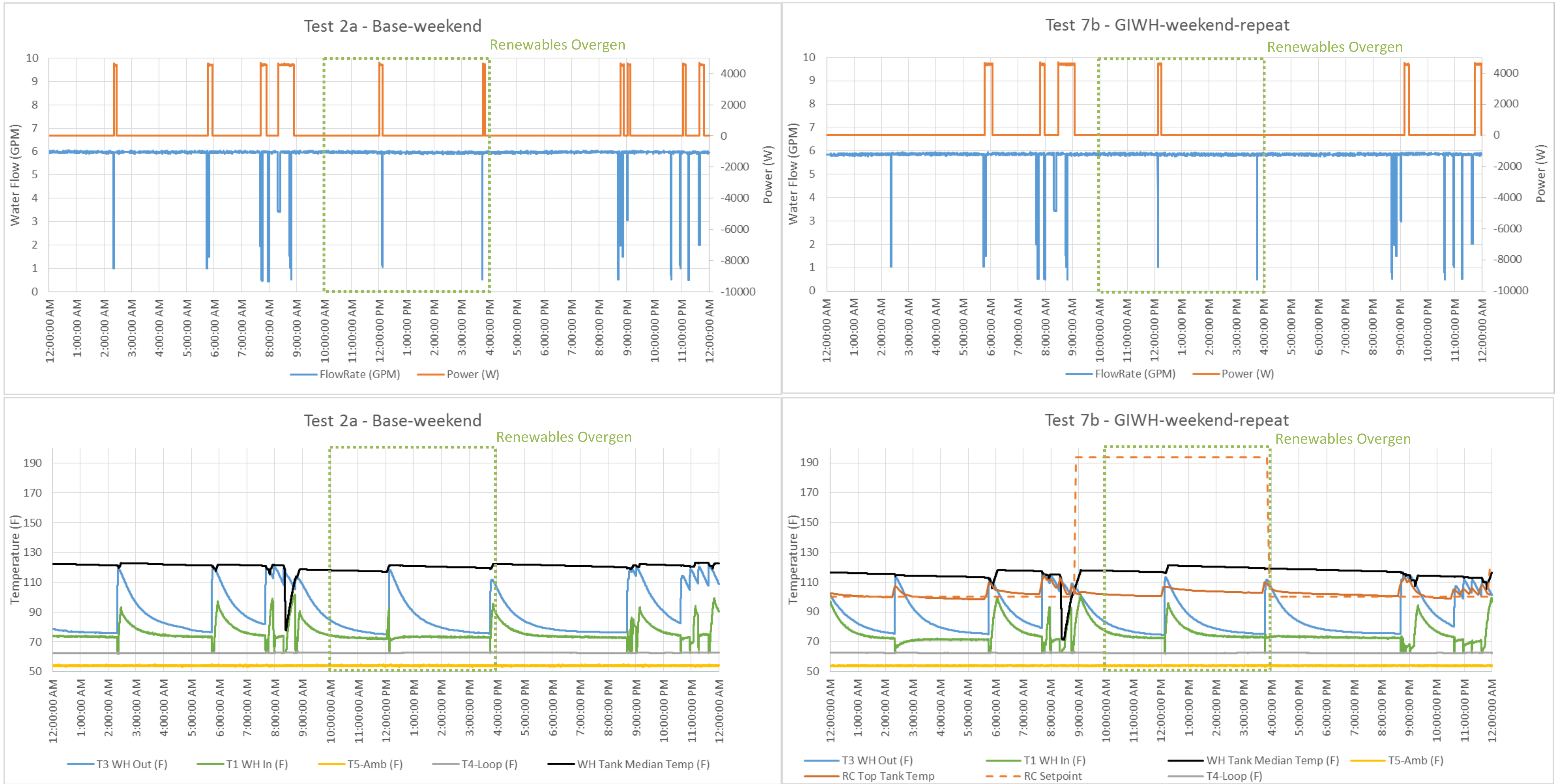


Figure 48. Power, Flow, and Temperatures – Comparing Baseline vs GIWH Controls Tests 2a and 7b

TABLE 18. WEEKEND GIWH CONTROLS TESTS – GIWH WINDOWS, TEST DATA AND % DEVIATIONS FROM BENCHMARK

Test	Time Period	Start Time	End Time	Energy (kWh)	Heater Runtime (min)	WH Tank Average Median Temp	WH Tank Median Temp - Start (F)	WH Tank Median Temp - End (F)
2a	Non-Overgen	12:00 AM	10:00 AM	4.8	62.3	120.1	122.4	118.0
7a				4.4	57.6	117.6	123.6	118.0
7b				4.8	62.7	114.0	116.3	117.8
2a	Renewables Overgen (CAISO Jan Weekend Super Off-Peak)	10:00 AM	4:00 PM	0.9	11.5	119.4	118.0	122.2
7a				0.5	6.7	119.3	118.0	119.2
7b				0.5	6.8	119.1	117.8	119.2
2a	Non-Overgen	4:00 PM	12:00 AM	2.3	29.8	121.3	122.2	122.4
7a				1.9	25.0	116.2	119.2	116.3
7b				1.9	25.0	116.1	119.2	116.1

Test	Time Period	Start Time	End Time	Energy (% Dev)	Heater Runtime (% Dev)	WH Tank Average Median Temp (% Dev)	WH Tank Median Temp - Start (% Dev)	WH Tank Median Temp - End (% Dev)
2a	Non-Overgen	12:00 AM	10:00 AM					
7a				-7%	-8%	-2%	1%	0%
7b				1%	1%	-5%	-5%	0%
2a	Renewables Overgen (CAISO Jan Weekend Super Off-Peak)	10:00 AM	4:00 PM					
7a				-41%	-42%	0%	0%	-2%
7b				-40%	-41%	0%	0%	-2%
2a	Non-Overgen	4:00 PM	12:00 AM					
7a				-16%	-16%	-4%	-2%	-5%
7b				-16%	-16%	-4%	-2%	-5%

TABLE 19. GIWH CONTROLS TEST DATA – PER-HOT WATER DRAW EVENT ANALYSIS WINDOW (WEEKEND PROFILE)

Sunday Draw Profile				2a	7a	7b	2a	7a	7b	2a	7a	7b	2a	7a	7b
Draw	Dur (min)	Time	Target GPM	Avg Flow Rate (GPM)			T1 WH In Avg Temp (F)			T3 WH Out Avg Temp (F)			WH Tank Avg Median Temp (F)		
1	2	2:20 AM	1	1.01	0.97	1.04	63.0	63.2	62.9	112.4	113.4	106.7	120.8	122.3	115.1
2	1	5:44 AM	1	1.01	1.05	1.05	63.9	63.9	63.5	104.5	105.1	100.0	120.9	119.6	112.9
3	3	5:46 AM	1.5	1.49	1.49	1.49	62.8	62.9	62.8	119.6	118.7	111.8	120.0	118.0	111.3
4	3	7:40 AM	2	1.95	1.97	1.98	63.1	63.0	63.0	117.1	113.4	114.0	120.1	107.6	116.6
5	1	7:43 AM	0.5	0.53	0.55	0.53	62.8	62.8	62.8	119.0	114.8	115.7	118.9	98.3	115.6
6	1	7:45 AM	0.5	0.48	0.51	0.52	64.4	63.9	63.7	118.5	114.3	115.2	118.6	98.5	115.2
7	1	7:57 AM	0.5	0.49	0.55	0.54	71.8	71.3	69.4	117.7	112.1	113.1	121.6	111.3	114.4
8	1	7:59 AM	0.5	0.46	0.54	0.52	65.7	65.5	65.0	120.1	112.9	114.3	121.5	113.4	115.3
9	5	8:19 AM	3.5	3.45	3.39	3.42	63.0	63.2	63.0	118.6	114.1	112.6	106.6	103.2	100.2
10	1	8:44 AM	1.5	1.52	1.52	1.51	70.3	68.7	68.4	111.1	109.3	107.7	112.5	101.3	99.7
11	1	8:46 AM	1	1.03	1.03	1.02	64.2	63.9	63.6	112.0	110.5	108.8	113.4	102.4	101.1
12	1	8:48 AM	0.5	0.53	0.49	0.51	64.4	64.3	63.9	113.0	110.0	108.0	114.1	104.1	102.4
13	1	12:07 PM	1	1.06	1.04	1.02	67.4	63.7	63.6	108.8	102.7	102.1	121.3	116.8	116.6
14	1	3:45 PM	0.5	0.57	0.55	0.55	63.9	63.9	63.9	90.0	82.5	89.9	119.4	119.4	119.5
15	1	8:41 PM	0.5	0.56	0.53	0.56	63.7	63.8	63.6	92.1	94.6	101.9	119.8	116.8	116.6
16	1	8:46 PM	2	2.00	1.96	1.97	64.1	64.0	63.8	117.9	114.8	115.2	119.4	116.3	116.1
17	1	8:51 PM	1.5	1.48	1.48	1.49	66.5	63.3	63.1	118.9	115.2	115.4	119.6	115.4	115.3
18	1	9:01 PM	3	3.05	3.01	3.02	64.8	63.3	63.1	119.4	114.2	114.2	121.0	113.4	113.3
19	1	10:37 PM	0.5	0.55	0.58	0.53	64.0	63.9	63.7	95.8	90.8	89.4	121.2	114.0	113.9
20	1	10:57 PM	1	1.02	1.03	1.03	64.1	63.8	63.8	115.2	108.2	107.9	120.8	113.8	113.6
21	1	11:15 PM	0.5	0.53	0.52	0.56	68.1	63.5	63.3	117.0	108.8	108.6	122.9	113.4	113.0
22	3	11:37 PM	2	1.99	1.99	2.01	63.3	63.1	63.0	120.8	111.5	111.2	122.0	112.2	112.0

Sunday Draw Profile				2a	7a	7b	2a	7a	7b	2a	7a	7b	2a	7a	7b
Draw	Dur (min)	Time	Target GPM	Avg Flow Rate (% Dev)			T1 WH In Avg Temp (% Dev)			T3 WH Out Avg Temp (% Dev)			WH Tank Avg Median Temp (% Dev)		
1	2	2:20 AM	1		-3%	4%		0%	0%		1%	-5%		1%	-5%
2	1	5:44 AM	1		4%	4%		0%	-1%		1%	-4%		-1%	-7%
3	3	5:46 AM	1.5		0%	-1%		0%	0%		-1%	-6%		-2%	-7%
4	3	7:40 AM	2		1%	1%		0%	0%		-3%	-3%		-10%	-3%
5	1	7:43 AM	0.5		2%	-1%		0%	0%		-3%	-3%		-17%	-3%
6	1	7:45 AM	0.5		8%	10%		-1%	-1%		-4%	-3%		-17%	-3%
7	1	7:57 AM	0.5		12%	10%		-1%	-3%		-5%	-4%		-8%	-6%
8	1	7:59 AM	0.5		17%	14%		0%	-1%		-6%	-5%		-7%	-5%
9	5	8:19 AM	3.5		-2%	-1%		0%	0%		-4%	-5%		-3%	-6%
10	1	8:44 AM	1.5		0%	-1%		-2%	-3%		-2%	-3%		-10%	-11%
11	1	8:46 AM	1		0%	-1%		0%	-1%		-1%	-3%		-10%	-11%
12	1	8:48 AM	0.5		-7%	-4%		0%	-1%		-3%	-4%		-9%	-10%
13	1	12:07 PM	1		-2%	-4%		-5%	-6%		-6%	-6%		-4%	-4%
14	1	3:45 PM	0.5		-4%	-4%		0%	0%		-8%	0%		0%	0%
15	1	8:41 PM	0.5		-6%	0%		0%	0%		3%	11%		-3%	-3%
16	1	8:46 PM	2		-2%	-1%		0%	-1%		-3%	-2%		-3%	-3%
17	1	8:51 PM	1.5		0%	1%		-5%	-5%		-3%	-3%		-4%	-4%
18	1	9:01 PM	3		-1%	-1%		-2%	-3%		-4%	-4%		-6%	-6%
19	1	10:37 PM	0.5		5%	-3%		0%	-1%		-5%	-7%		-6%	-6%
20	1	10:57 PM	1		1%	1%		0%	0%		-6%	-6%		-6%	-6%
21	1	11:15 PM	0.5		-2%	6%		-7%	-7%		-7%	-7%		-8%	-8%
22	3	11:37 PM	2		0%	1%		0%	0%		-8%	-8%		-8%	-8%

Observations: Figure 47, Figure 48, Table 18, and Table 19 (Tests 7a and 7b vs benchmark Test 2a)

Analysis window normalized to each TOU period.

- During the Non-Overgeneration period (12:00 AM – 10:00 AM):
    - -7% and -8% deviations in energy consumption and heater runtimes, respectively, for Test 6a.
    - 1% deviations in energy consumption and heater runtimes, respectively, for Test 6b.
    - Average starting and ending median tank temperatures saw deviations within 5% for Test 6a and 6b.
- During the Overgeneration period (10:00 AM – 4:00 PM):
    - -41% and -42% deviations in energy consumption and heater runtimes, respectively, for Test 6a.
    - -40% and -41% deviations in energy consumption and heater runtimes, respectively, for Test 6b.
    - Average starting and ending median tank temperatures saw deviations within 2%.
- During the Non-Overgeneration period (4:00 PM – 12:00 AM):
    - -16% deviations in energy consumption and heater runtimes for Test 6a and Test 6b.
    - Average starting and ending median tank temperatures saw deviations within 5% for Test 6a and Test 6b.

Analysis window normalized to every hot water draw event.

- For the average water flow rates the deviations were within 17%.
    - Deviations were within 4% for events with target flow rates above 0.5 gpm.
- For the T1 average inlet water temperatures deviations were within 7%.
- For the T3 average outlet water temperatures deviations were within 11%.
- For the average median tank temperatures deviations were within 17%.

Discussion: Figure 47, Figure 48, Table 18, and Table 19 (Tests 7a and 7b vs benchmark Test 2a)

The approximated GIWH controls reduced energy consumption during non-overgeneration periods and showed baseline operation during the generation period.

The non-overgeneration periods were approximated with “load shift” events, which lower the setpoint temperature of the retrofit controller. Even though the mechanical thermostats may be calling for heating, the retrofit controller can intercept and prevent heating from occurring with its lowered setpoint.

The overgeneration period was approximated with a “boost” event, which raised the retrofit controller’s setpoint. However, in this case heating operation was limited by the mechanical thermostat. Although the retrofit controller was calling for heating throughout the overgeneration period, the mechanical thermostat controls were satisfied, so no alteration to the heating operation occurs. The retrofit controls can intercept and avoid a heating cycle that is occurring due to mechanical controls, but it cannot force a heating cycle to come on if the mechanical controls are off/satisfied.

The reduction in energy during the overgeneration period is likely a result of inconsistency in the mechanical thermostat controls and the low baseline usage during the overgeneration period means that % deviations simply appear more pronounced.

DETAILED TANK TEMPERATURES AND ENERGY ANALYSIS – ALL TESTS

FIGURE 49. WATER HEATER TANK TEMPERATURES, TESTS 1A – 1C, AND TEST 3

FIGURE 50. WATER HEATER TANK TEMPERATURES, TESTS 2A – 2C

FIGURE 51. WATER HEATER TANK TEMPERATURES, TESTS 4A – 5B

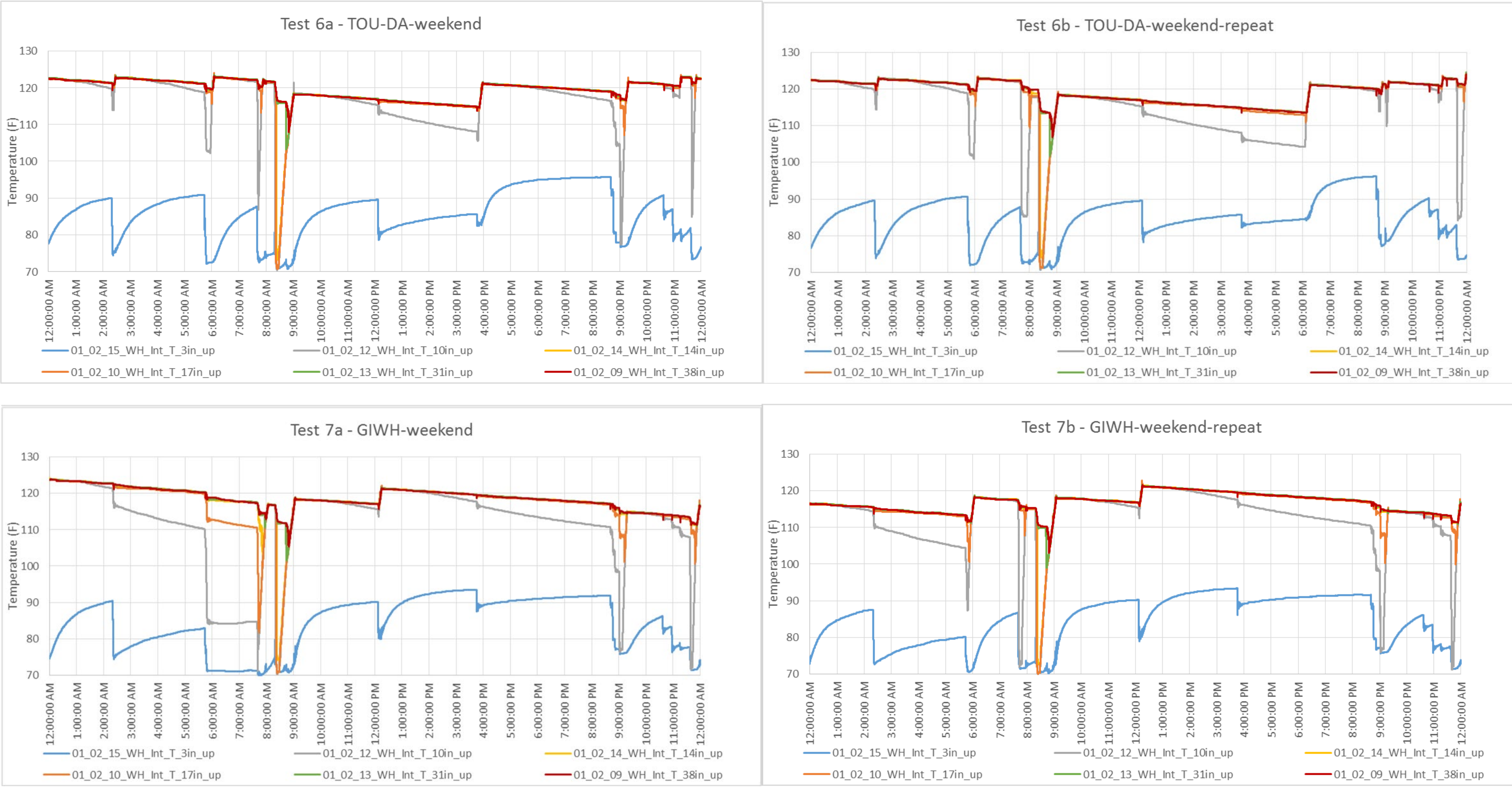


FIGURE 52. WATER HEATER TANK TEMPERATURES, TESTS 6A – 7B

TABLE 20. WATER HEATER DAILY AVERAGE MEDIAN, MINIMUM, AND MAXIMUM TEMPERATURES – DAILY ANALYSIS WINDOW

Date	Test #		Description	WH Whole Tank Daily Avg Med	WH Whole Tank Daily Max	WH Whole Tank Daily Min	WH Temp - 3" Daily Max	WH Temp - 3" Daily Min	WH Temp - 10" Daily Max	WH Temp - 10" Daily Min	WH Temp - 14" Daily Max	WH Temp - 14" Daily Min	WH Temp - 17" Daily Max	WH Temp - 17" Daily Min	WH Temp - 31" Daily Max	WH Temp - 31" Daily Min	WH Temp - 38" Daily Max	WH Temp - 38" Daily Min
4/10/2018	1	a	Base-weekday	121.9	125.1	75.7	106.6	75.7	124.6	93.1	124.8	117.1	125.1	112.6	124.8	117.5	124.5	116.9
4/11/2018		b	Base-weekday-repeat	122.9	125.4	75.9	98.4	75.9	125.0	93.6	125.0	119.8	125.4	117.7	125.1	120.7	124.9	120.0
4/13/2018		c	Base-weekday-repeat	122.0	125.9	75.6	104.5	75.6	124.8	93.6	124.6	117.9	125.9	113.1	124.9	118.0	124.3	117.5
4/18/2018	3	-	Base, Ret Ctrl On	122.3	124.9	75.4	97.9	75.4	124.4	91.0	124.4	119.5	124.9	116.1	124.4	119.8	124.2	118.9
4/19/2018	4	a	Load Curtailment-weekday	122.4	125.5	74.9	97.6	74.9	124.8	91.7	124.6	119.8	125.5	116.1	124.7	120.0	124.6	119.3
4/20/2018		b	Load Curtailment-weekday-repeat	122.6	125.5	75.5	97.9	75.5	124.6	91.2	124.6	120.1	125.5	117.4	125.1	120.4	124.5	119.3
4/21/2018	5	a	TOU-DA-weekday	122.4	126.5	75.2	97.6	75.2	126.5	91.2	124.4	120.2	124.5	117.1	124.7	120.6	124.3	119.4
4/22/2018		b	TOU-DA-weekday-repeat	122.0	124.5	75.0	97.3	75.0	124.1	91.0	124.0	119.5	124.5	115.7	123.9	119.8	123.8	119.0
4/14/2018	2	a	Base-weekend	120.3	123.6	72.7	97.0	72.7	123.2	75.1	123.4	78.6	123.6	76.2	123.3	104.7	123.4	111.9
4/15/2018		b	Base-weekend-repeat	120.2	124.1	72.3	100.4	72.3	123.3	74.7	123.3	78.4	124.1	75.7	123.9	105.1	123.4	112.0
4/16/2018		c	Base-weekend-repeat	120.3	124.2	72.4	97.1	72.4	123.4	74.6	123.3	77.7	124.2	76.0	123.8	105.3	123.2	112.7
4/24/2018	6	a	TOU-DA-weekend	119.0	124.0	70.4	95.7	70.7	123.1	70.4	123.1	73.2	124.0	70.8	123.5	103.2	123.1	108.0
4/25/2018		b	TOU-DA-weekend-repeat	118.6	124.6	70.6	96.2	71.0	124.1	70.6	124.3	73.8	124.5	71.2	124.6	101.7	124.0	106.8
4/26/2018	7	a	GIWH-weekend	117.5	124.1	69.7	93.5	69.7	123.8	70.4	124.1	73.4	123.7	70.6	123.8	101.5	123.8	105.3
4/27/2018		b	GIWH-weekend-repeat	116.0	122.9	69.9	93.4	70.2	121.3	69.9	121.6	72.6	122.9	70.1	121.6	99.0	121.5	103.1

Date	Test #		Description	WH Whole Tank Daily Avg Med	WH Whole Tank Daily Max (% Dev)	WH Whole Tank Daily Min (% Dev)	WH Temp - 3" Daily Max (% Dev)	WH Temp - 3" Daily Min (% Dev)	WH Temp - 10" Daily Max (% Dev)	WH Temp - 10" Daily Min (% Dev)	WH Temp - 14" Daily Max (% Dev)	WH Temp - 14" Daily Min (% Dev)	WH Temp - 17" Daily Max (% Dev)	WH Temp - 17" Daily Min (% Dev)	WH Temp - 31" Daily Max (% Dev)	WH Temp - 31" Daily Min (% Dev)	WH Temp - 38" Daily Max (% Dev)	WH Temp - 38" Daily Min (% Dev)
4/10/2018	1	a	Base-weekday															
4/11/2018		b	Base-weekday-repeat	1%	0%	0%	-8%	0%	0%	1%	0%	2%	0%	4%	0%	3%	0%	3%
4/13/2018		c	Base-weekday-repeat	0%	1%	0%	-2%	0%	0%	1%	0%	1%	1%	1%	0%	0%	0%	1%
4/18/2018	3	-	Base, Ret Ctrl On	0%	0%	0%	-8%	0%	0%	-2%	0%	2%	0%	3%	0%	2%	0%	2%
4/19/2018	4	a	Load Curtailment-weekday	0%	0%	-1%	-9%	-1%	0%	-1%	0%	2%	0%	3%	0%	2%	0%	2%
4/20/2018		b	Load Curtailment-weekday-repeat	1%	0%	0%	-8%	0%	0%	-2%	0%	3%	0%	4%	0%	2%	0%	2%
4/21/2018	5	a	TOU-DA-weekday	0%	1%	-1%	-9%	-1%	2%	-2%	0%	3%	0%	4%	0%	3%	0%	2%
4/22/2018		b	TOU-DA-weekday-repeat	0%	0%	-1%	-9%	-1%	0%	-2%	-1%	2%	0%	3%	-1%	2%	-1%	2%
4/14/2018	2	a	Base-weekend															
4/15/2018		b	Base-weekend-repeat	0%	0%	-1%	3%	-1%	0%	-1%	0%	0%	0%	-1%	1%	0%	0%	0%
4/16/2018		c	Base-weekend-repeat	0%	0%	0%	0%	0%	0%	-1%	0%	-1%	0%	0%	0%	1%	0%	1%
4/24/2018	6	a	TOU-DA-weekend	-1%	0%	-3%	-1%	-3%	0%	-6%	0%	-7%	0%	-7%	0%	-1%	0%	-4%
4/25/2018		b	TOU-DA-weekend-repeat	-1%	1%	-3%	-1%	-2%	1%	-6%	1%	-6%	1%	-7%	1%	-3%	0%	-5%
4/26/2018	7	a	GIWH-weekend	-2%	0%	-4%	-4%	-4%	1%	-7%	1%	-7%	0%	-8%	0%	-3%	0%	-6%
4/27/2018		b	GIWH-weekend-repeat	-4%	-1%	-4%	-4%	-3%	-2%	-7%	-1%	-8%	-1%	-8%	-1%	-6%	-2%	-8%

Note: Daily **maximum** and **minimum** water temperature values within the water heater are emphasized per test.

Observations and Discussion: Figure 49 through Figure 52 and Table 20

- Generally, temperature measurements besides the lowest height, grouped fairly close together.
- Generally for all tests, the temperature measured at a height of 3 inches consistently had the lowest values, with the exception of Tests 6a, 6b, and 7b, where the minimums occurred at the 10-inch height.
- The temperature measured at the height of 17 inches generally had the maximum values across all tests, with the exception of tests 5a, 6b, and 7a, where the maximums occurred at the 10-inch, 31-inch, and 14-inch heights, respectively.
- In Test 3, the presence of the retrofit controller under the baseline fixed setpoint operation did not have an appreciable impact on the maximum and minimum temperatures observed in the water heater.
- The retrofit controller operating under schemes ranging from load curtailment, TOU, and GIWH, resulted in negligible impacts (within 2% deviation) on maximum water temperatures observed in the tank. Under those control schemes the minimum observed water temperatures in the tank had mild deviations as much as -9%.

HEAT/ENERGY RUNNING TOTALS CHARTS – ALL TESTS

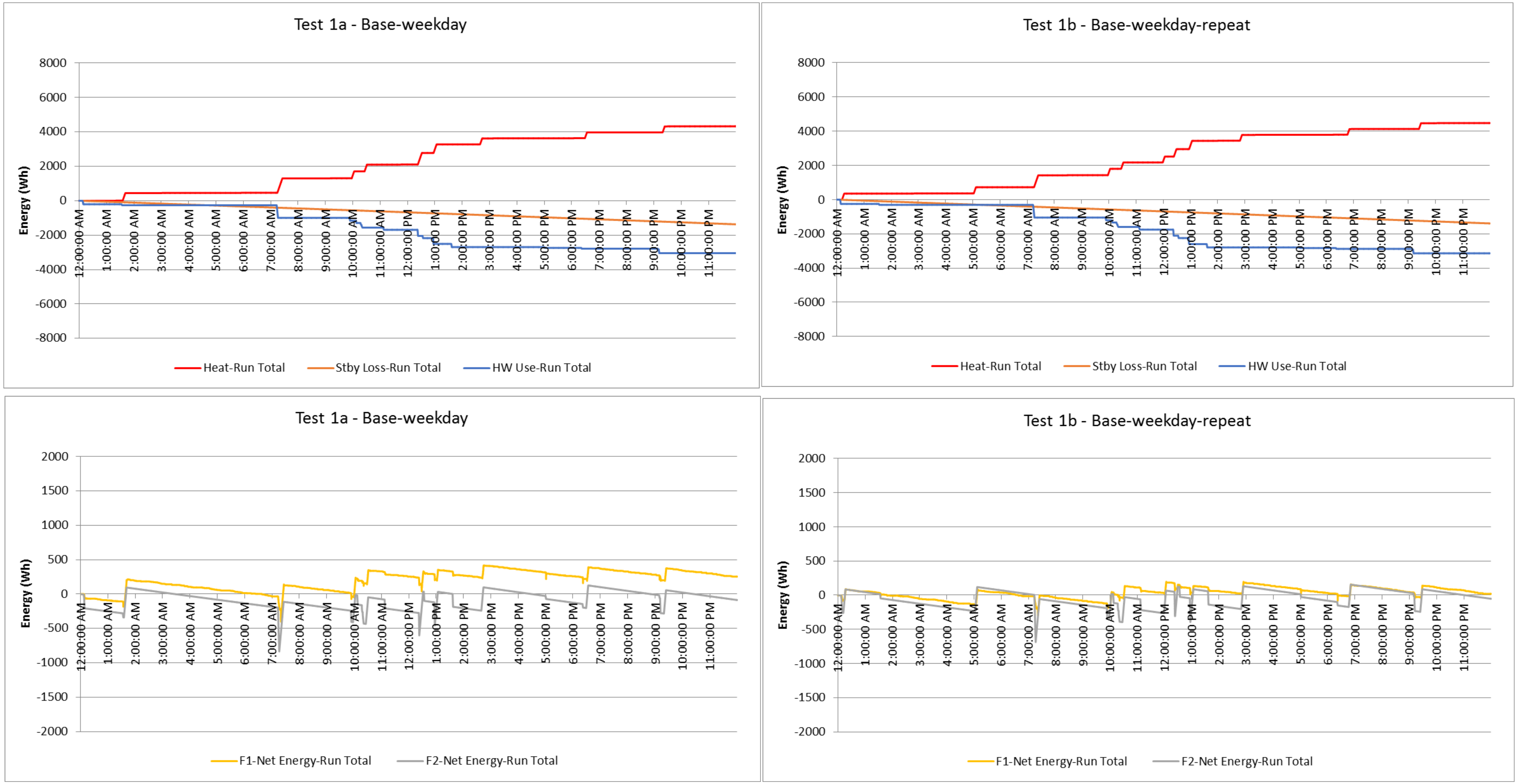


FIGURE 53. HEAT AND ENERGY RUN TOTALS (TESTS 1A AND 1B)

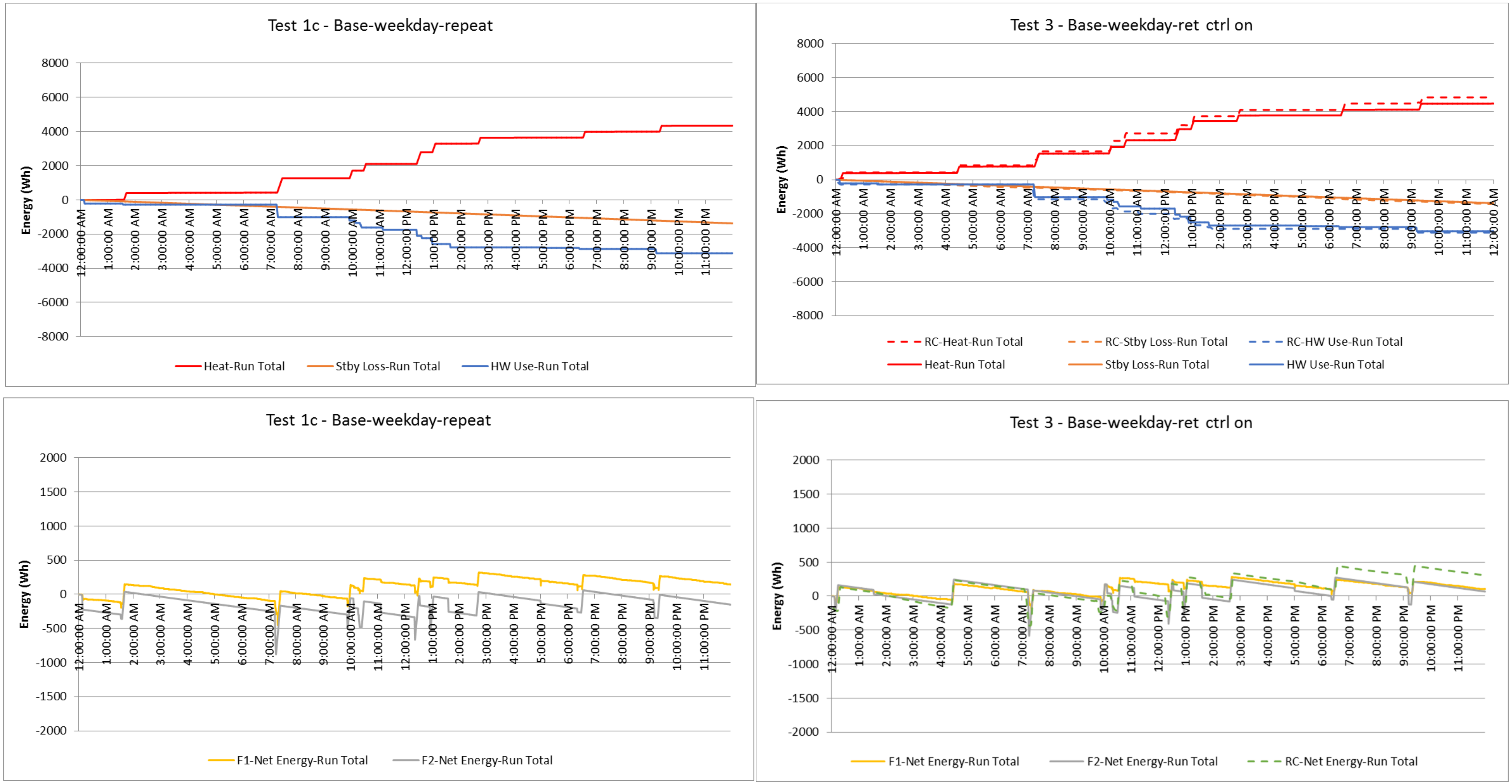


FIGURE 54. HEAT AND ENERGY RUN TOTALS (TEST 1C AND TEST 3)

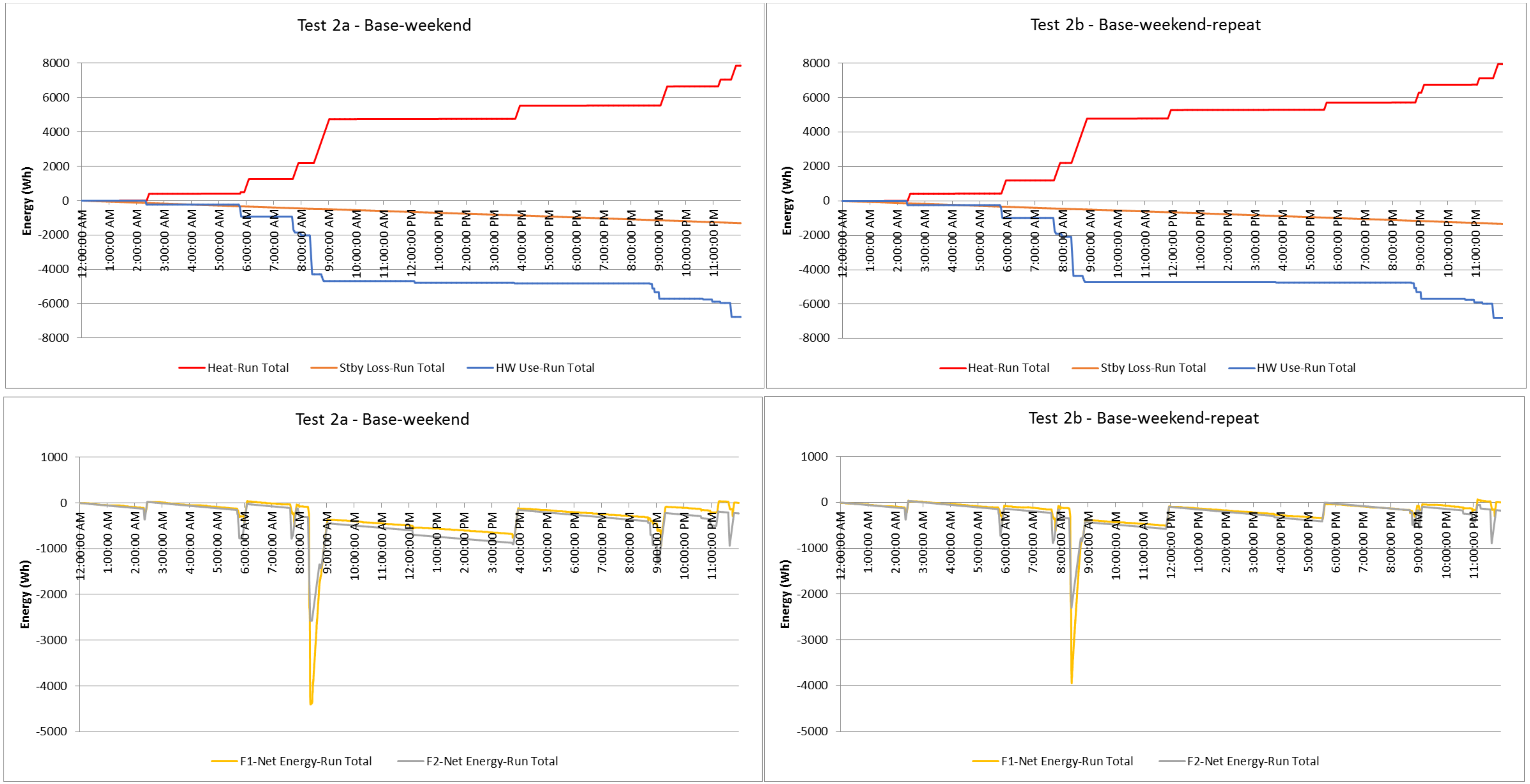
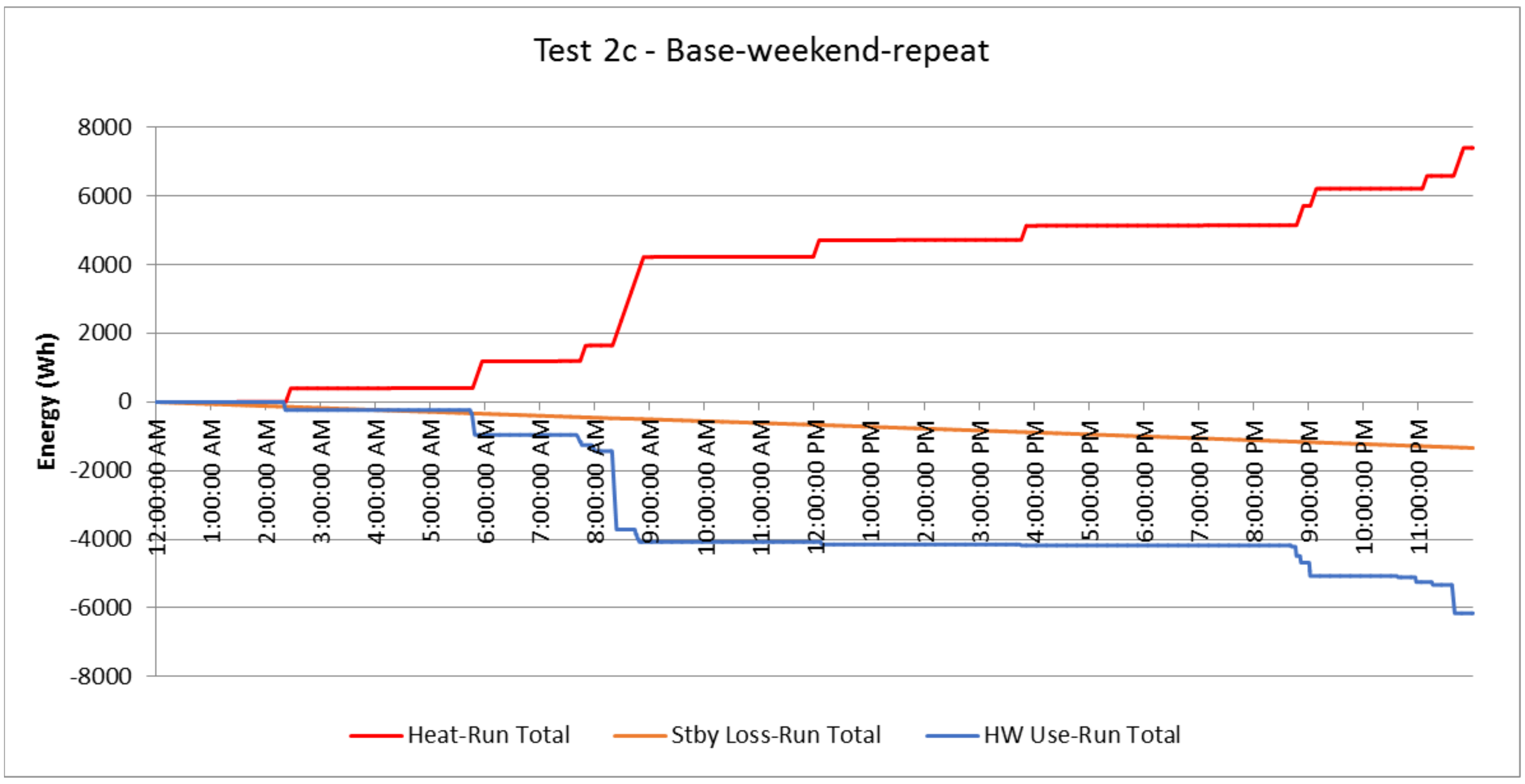


FIGURE 55. HEAT AND ENERGY RUN TOTALS (TESTS 2A AND 2B)



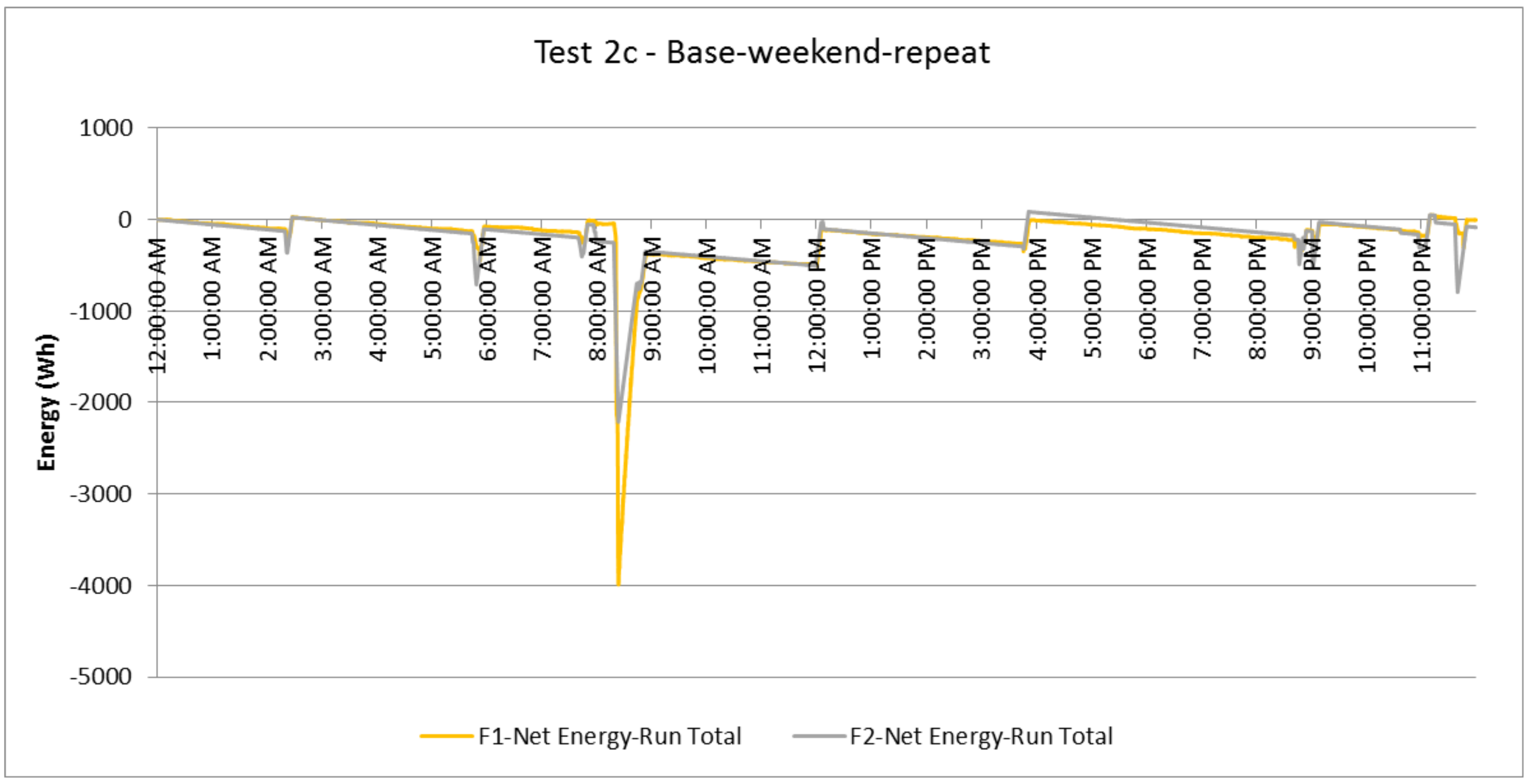


FIGURE 56. HEAT AND ENERGY RUN TOTALS (TEST 2C)

Observations and Discussion: Figure 53 through Figure 56

- Net energy balance equations F1 and F2 across baseline Tests 1 – 3, based on lab measurements show slight variance, when examining the 24-hour shapes. Both equations are used and illustrated in running totals. These running totals may accumulate "stacking" uncertainties of the measurements that feed into them, as they are summed over the 24-hour period with 1-second sampling rate.
- The running total net energy balance is observed to hover around 0 for the baseline Tests 1-3. This is expected as a water heater should be in constant fluctuating states of losing energy and recovering lost energy. Under the weekday profile baseline test conditions, the "deadband" of energy fluctuations resides at approximately +/- 500Wh. The weekend profile baseline test conditions resulted in more pronounced drop-offs/recovery in net energy running totals.
- Test 3 illustrates reasonable agreement between energy losses/gains calculated by the methods/measurements from the lab and the retrofit controller. The running totals illustrated, based on the retrofit controller calculations may also accumulate "stacking" uncertainties of the measurements that feed into them, as they are summed over the 24-hour period with 5-minute sampling rate.

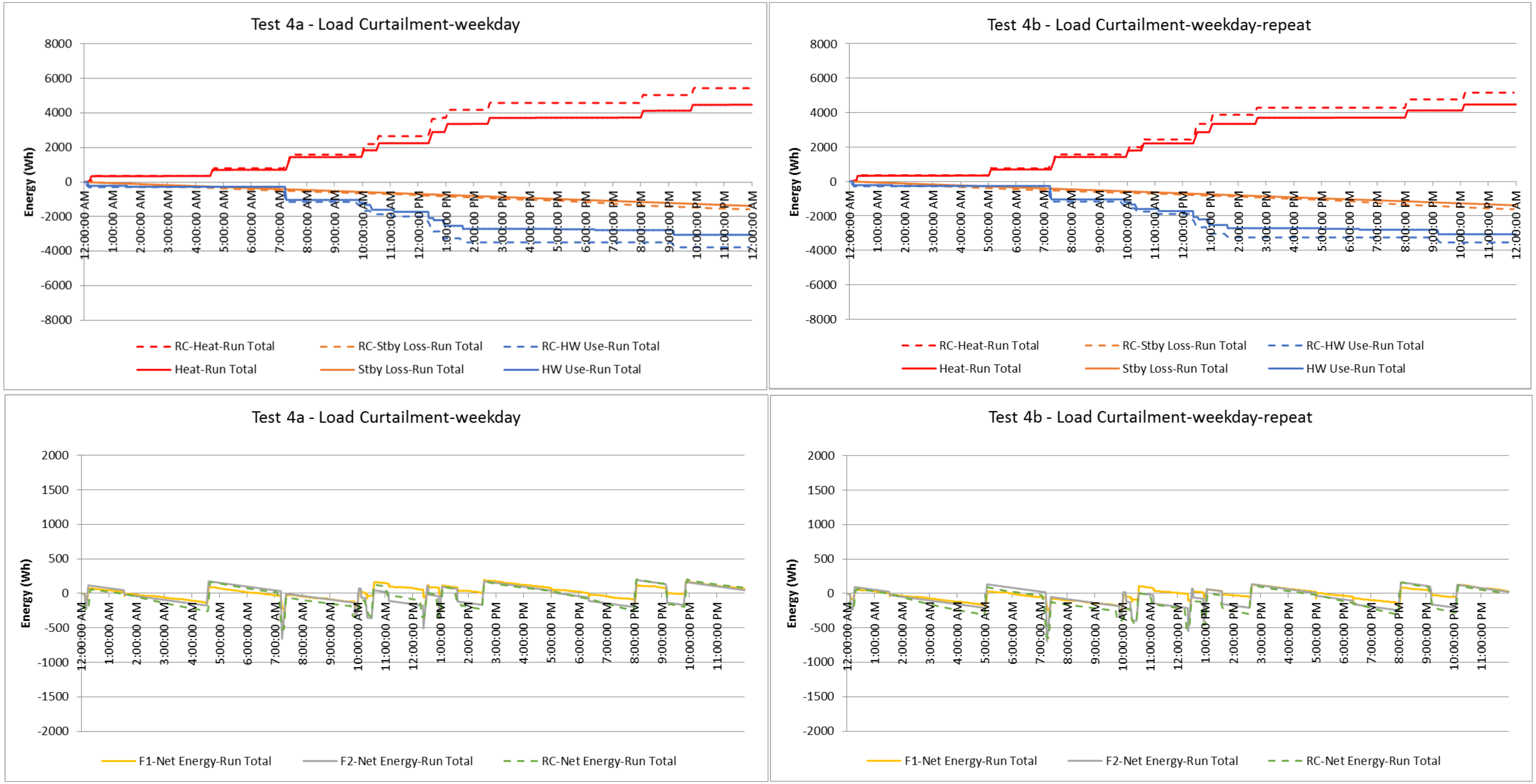


Figure 57. Heat and Energy Run Totals (Tests 4a and 4b)

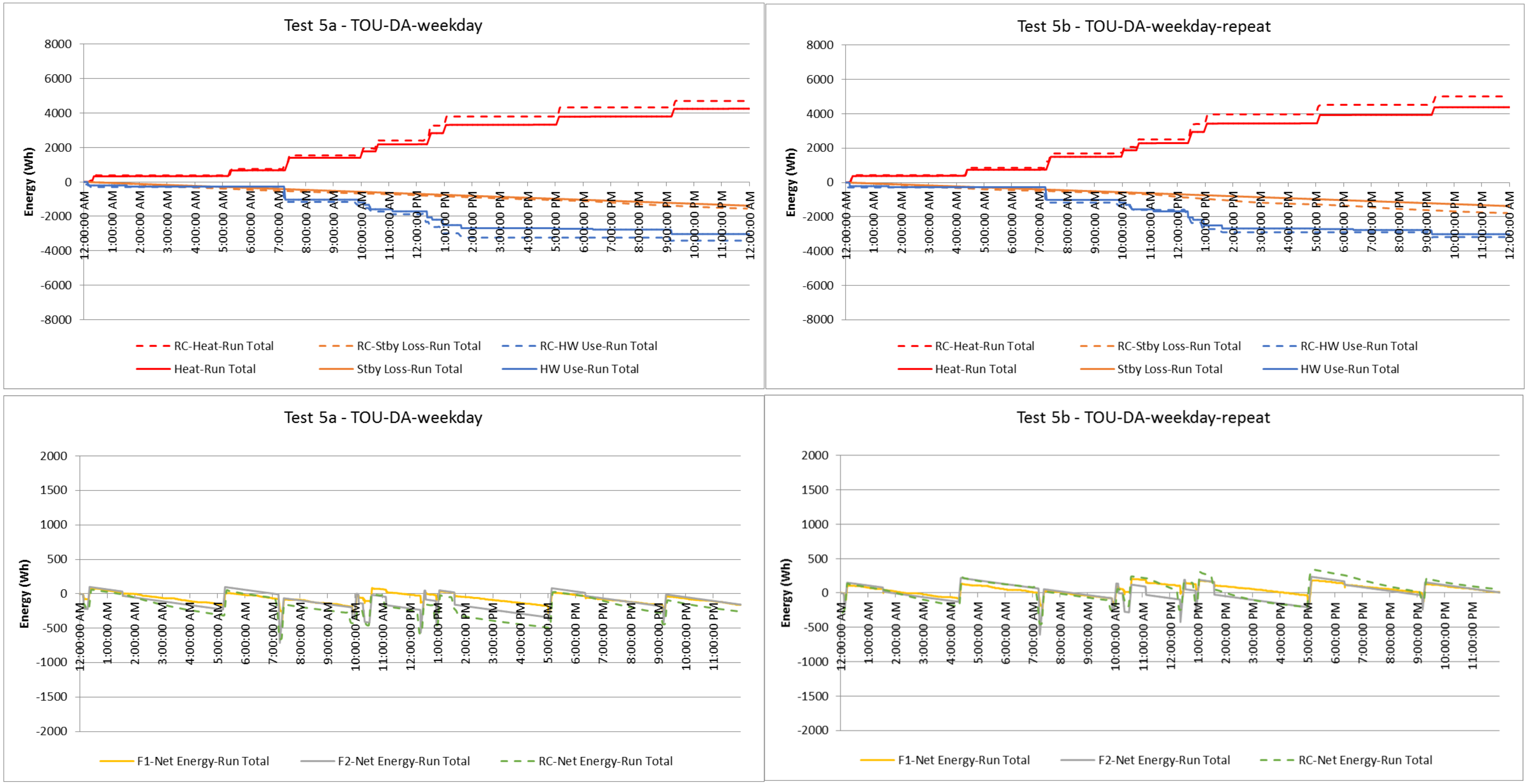


FIGURE 58. HEAT AND ENERGY RUN TOTALS (TESTS 5A AND 5B)

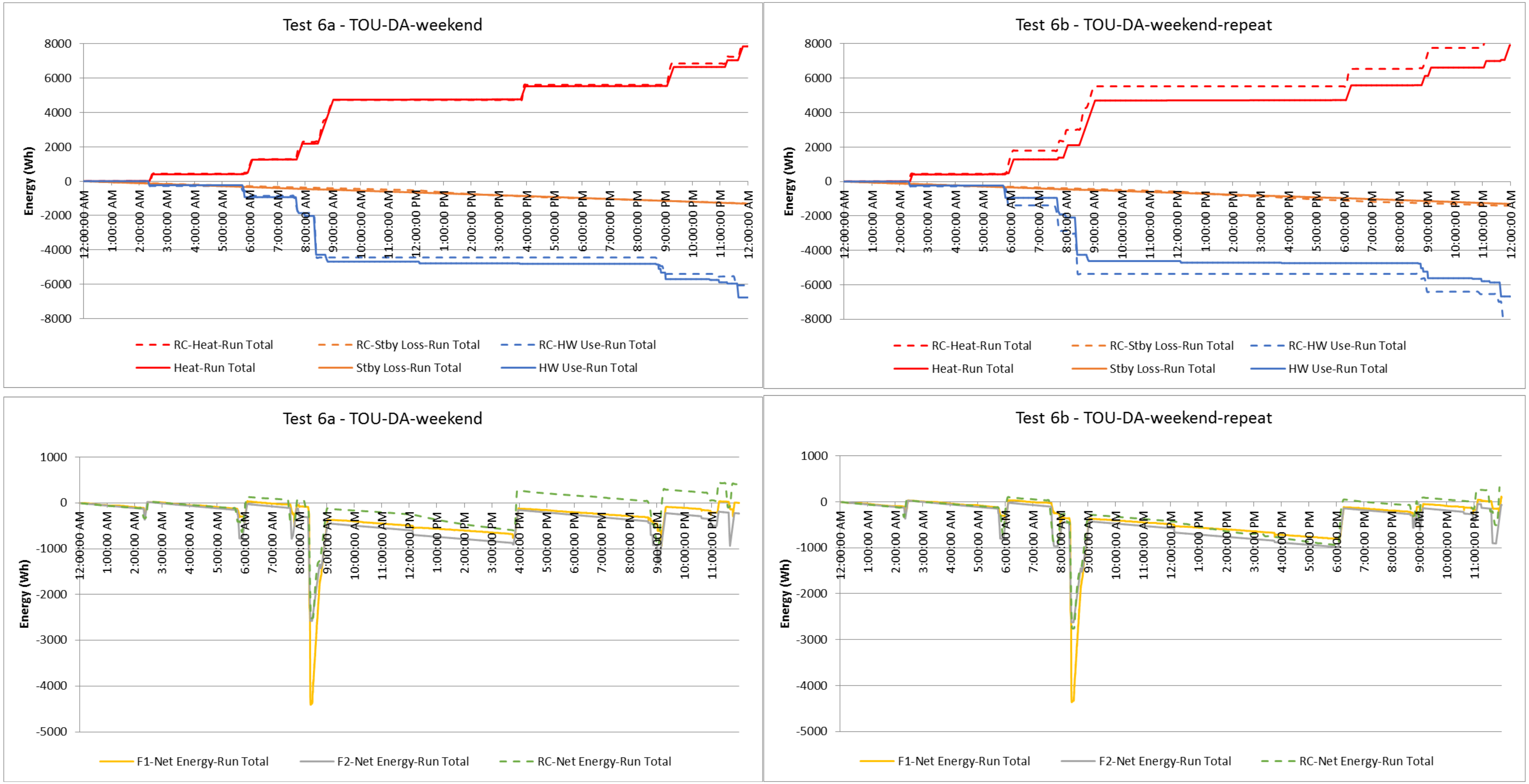


FIGURE 59. HEAT AND ENERGY RUN TOTALS (TESTS 6A AND 6B)

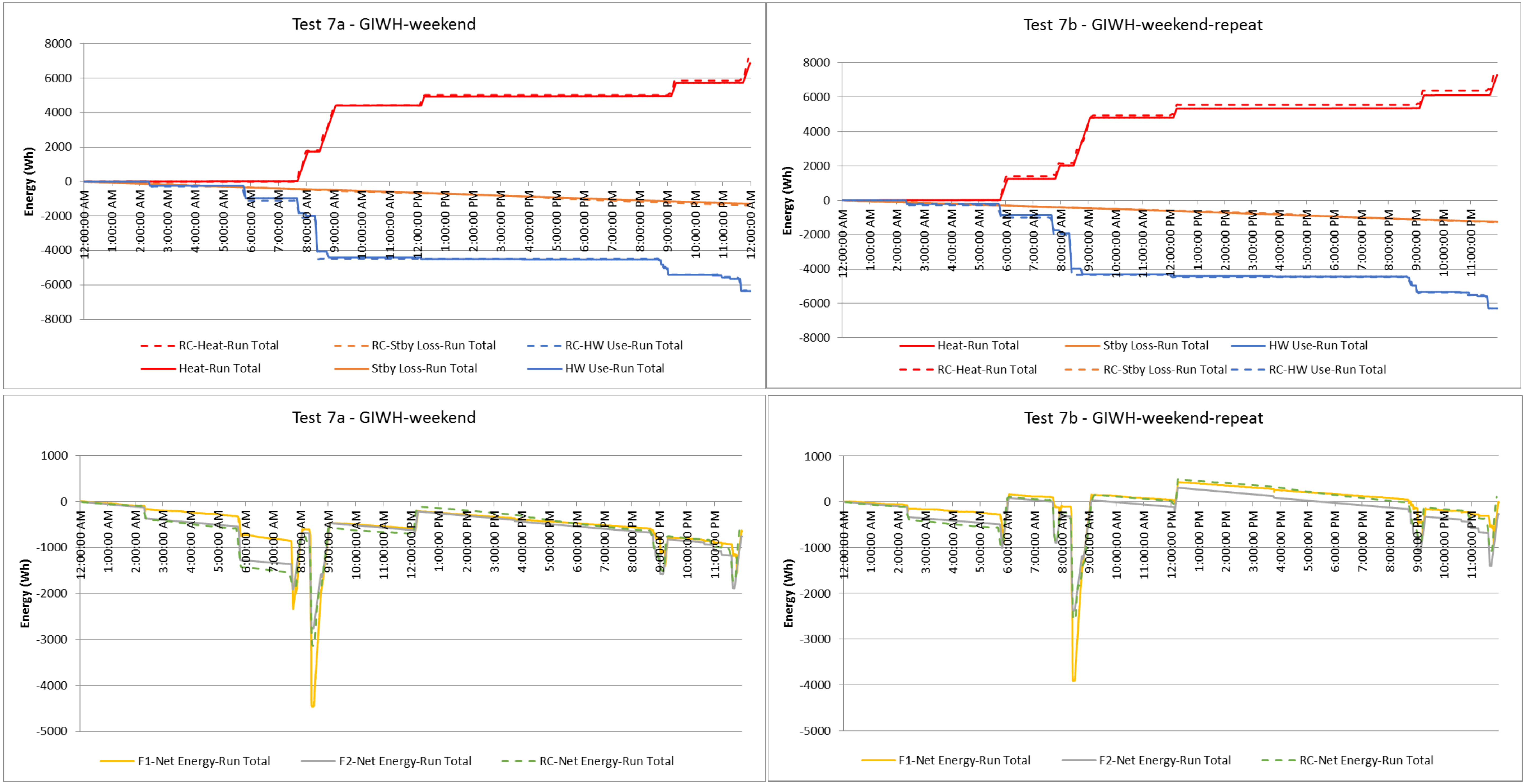


Figure 60. Heat and Energy Run Totals (Tests 7a and 7b)

Observations and Discussion: Figure 57 through Figure 60

- Net energy balance equations F1 and F2 across baseline Tests 4 – 7, based on lab measurements show slight variance, when examining the 24- hour shapes. Both equations are used and illustrated in running totals. These running totals may accumulate “stacking” uncertainties of the measurements that feed into them, as they are summed over the 24-hour period with 1-second sampling rate.
- The running total net energy balance is observed to hover around 0 for Tests 4-7. This is expected as a water heater should be in constant fluctuating states of losing energy and recovering lost energy. Under the weekday profile tests (Tests 4 and 5), the “deadband” of energy fluctuations resides at approximately +/- 500Wh. The weekend profile tests resulted in more pronounced drop-offs/recovery in net energy running totals.
- Test 3 illustrates reasonable agreement between energy losses/gains calculated by the methods/measurements from the lab and the retrofit controller. The running totals illustrated, based on the retrofit controller calculations may also accumulate “stacking” uncertainties of the measurements that feed into them, as they are summed over the 24hour period with 5-minute sampling rate.

CONCLUSIONS

Demand response controls for water heaters present great opportunities for GHG reduction and grid management. However, it involves complex interactions that should be well-understood in order to successfully operate demand response programs for water heaters. This laboratory study offers detailed insight into the complex interactions that can take place in a water heater. A continuous balance must be maintained between meeting hot water needs, mitigating safety concerns for scalding and pathogen development, and managing energy use. This investigation confirmed that this technology shows promise to enable utility programs to implement the three main DR strategies identified, with some given nuances that can be addressed:

- **Load Curtailment:** Load curtailment may be scheduled through the internet-based fleet dashboard as single load curtailment events or recurring load shift events. Single load curtailment events can force the water heater to shut off heating or modify temperature setpoint of the retrofit controller. Recurring load shift events did not offer the selection between setpoint and heating shut-off. The fleet dashboard is suitable for use by program implementers, but it is likely that communication of load curtailment events for high volumes of products is preferred through interaction with utility demand response automation servers via openADR. Utilities should work with controls manufacturers to ensure an appropriate communication pathway is established.
- **TOU Controls:** At the time of this project, all SCE TOU rates could be configured into the TOU controls of the retrofit controls product, but only through the user portal. There did not appear to be any other telemetry/monitoring to confirm the TOU schedule that was selected. Utilities should work with controls manufacturers to ensure an appropriate communication pathway is established for setting and verification of appropriate TOU controls.
- **GIWH:** This is not a selectable mode in either the user portal or the fleet dashboard. It was approximated using available fleet dashboard/user portal means. At the time of this project, it was approximated with load curtailment from the fleet dashboard, in conjunction with temperature boost scheduling configured in the user portal. It is unclear what utility grid condition telemetry would best feed into the product in order to inform real-time GIWH operation and how those signals will be communicated. Utilities should work with controls manufacturers to ensure an appropriate communication pathway is established and controls schemes are informed with the appropriate telemetry.

The research questions first posed at the outset of this study are answered as follows:

4. What are the demand savings benefits of the identified DR control schemes?

   Water heaters come in a variety of sizes and types for residential applications. The baseline water heater established in this study had two 4.5 kW heating elements that are never on at the same time. Total peak demand of the water heater was therefore 4.5 kW. This peak can be curtailed or shifted with the retrofit controls product with the DR schemes identified. However, under even baseline operation, the timing of heating events will vary based on hot water usage and the inherent inconsistencies in the water heater’s mechanical controls. Additionally, heating element runtimes are fairly short occurrences throughout the 24-hour test period. Total heating runtimes under baseline operation were 56 minutes per day for the weekday profile Test 1a and 104 minutes per day for the weekend profile Test 2a.

5. What happens to water heater thermal performance for the identified DR control schemes?

   a. What are the average/maximum/minimum water temperatures in the water heater tank under typical usage, with and without, the retrofit controls?

Test #		Description	WH Whole Tank Daily Avg Med	Daily Max	Daily Min
1	a	Base-weekday	121.9	125.1	75.7
	b	Base-weekday-repeat	122.9	125.4	75.9
	c	Base-weekday-repeat	122.0	125.9	75.6
3	-	Base, Ret Ctrl On	122.3	124.9	75.4
4	a	Load Curtailment-weekday	122.4	125.5	74.9
	b	Load Curtailment-weekday-repeat	122.6	125.5	75.5
5	a	TOU-DA-weekday	122.4	126.5	75.2
	b	TOU-DA-weekday-repeat	122.0	124.5	75.0
2	a	Base-weekend	120.3	123.6	72.7
	b	Base-weekend-repeat	120.2	124.1	72.3
	c	Base-weekend-repeat	120.3	124.2	72.4
6	a	TOU-DA-weekend	119.0	124.0	70.4
	b	TOU-DA-weekend-repeat	118.6	124.6	70.6
7	a	GIWH-weekend	117.5	124.1	69.7
	b	GIWH-weekend-repeat	116.0	122.9	69.9

   b. Under the DR control schemes, do the retrofit controls maintain water temperatures suitable to continue meeting the needs of typical home water usage?

   The retrofit controls appear to be capable of delivering hot water temperatures per hot water draw event, similar to those of baseline operation. The mild deviations of water heater outlet temperatures per hot water draw event were within the typical deviations observed during baseline repeat testing. Mild deviations were more frequent under the approximated GIWH controls, likely attributed to the mechanical thermostat limitations of the temperature boost feature, which are easily remedied. The retrofit controller generally makes determinations for maintaining a minimal amount of available hot water, regardless of the selected control scheme.

   c. Do the reduced water temperatures appreciably increase the risk of pathogen growth, such as legionella bacteria?

   The retrofit controls and associated DR schemes of operation do not appear to significantly increase risk of pathogen growth. The critical area appears to continue to be at the bottom of the water tank, where biofilms were originally understood to proliferate within this style of water heater. It is important to advocate for mitigation of these risks through best practices/manufacturer recommendations for water heater maintenance/flushing. The retrofit controls contain temperature boosting features that may be able to assist with controlling pathogen growth. Further studies on appropriate strategies should be considered.

d. Do any of the DR control schemes involve elevated water temperatures to increase/optimize energy storage or appreciably increase the risk of scalding?

The GIWH approximation (boost mode) did involve raising water heater setpoint. However, the effective setpoint was limited by the physical settings of the mechanical thermostat during testing. This can be easily addressed in practice. The water heater is certainly capable of producing scalding water temperatures both with and without the retrofit controller. These risks should be mitigated through use of mixing valves regardless of the presence of the retrofit controller, as required by plumbing code and informed by best design practices.

6. In terms of customer experience and interaction, what can be expected with the retrofit technology under each of the DR control schemes? Questions may include but are not limited to:

   a. Is Automated Demand Response (ADR) available/enabled for this retrofit technology? Explain.

   At the time of the project, this technology was not enabled to communicate through openADR. Demand response communication is handled using the internet-based fleet dashboard. Additional work is required to facilitate communication between this product and utility demand response automation servers.

   b. Is the interface easy to use? What are the customer options for overriding? Other noteworthy features?

   At the time of this project, the version of the user portal seemed clean and intuitive. TOU scheduling may appear confusing and tedious for consumers; therefore it is important that utilities mitigate the burden of adopting TOU controls as much as possible. Pre-loaded TOU rate schedules should be readily available and updated on an ongoing basis. For DR program implementers, monitoring/setting of TOU rates schedules can be available to ensure correct rates schedules are used. TOU controls can be easily enabled/disabled in the user portal.

   For load curtailment and load shift functions initiated from the fleet dashboard, the user portal indicates events once they are in progress. There did not appear to be any user override options or advanced notification of scheduled load curtailment/load shift events.

   Other noteworthy features not explored in this study are the hot water usage learning function, the three efficiency settings, the display of the water heater as a thermal battery with % capacity indication, and the historical tracking of energy & hot water usage.

RECOMMENDATIONS

Further studies should be pursued to establish more understanding of characterizing broader market offerings for retrofit controls and onboard controls. Classifications of product families should be established and pursued for DR program development. DR program requirements/specifications related to communications and DR scheme capabilities should be established.

Any demand response programs associated with water heaters should advocate industry-accepted best practices for ensuring safe operation, emphasizing mitigation of risks associated with scalding and pathogen growth. Best practices for maintenance should be emphasized. Opportunities for temperature-boost controls, leveraged as pathogen growth mitigation strategies should be explored.

Further studies should be pursued to establish an acceptable tool for predicting hot water usage, for water heater DR program use. Resources for T-24 energy modeling purposes, and the tool established for the DOE Building America program should be considered.

The challenges in addressing energy-conscious best practices for water heater sizing, and plumbing system design seem somewhat analogous to the HVAC industry. Water heater measures should always be conscious of the water heater and connected plumbing at the system level (just as optimal HVAC measures for RTUs should consider the entire attached duct system). The industry-accepted best practices/design do not appear to be as detailed and well-established as those in the HVAC industry (e.g., ACCA manuals, ASHRAE Handbooks, etc.). DR water heater programs should promote research and advocacy for standardizing energy-conscious best practices for water heater design and adopt those procedures as part of water heater DR program implementation.