Demand Response (DR) Heat Pump Water Heater (HPWH) Implementation in CBECC-Res

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1. Introduction

Southern California Edison (SCE) supported the California Energy Commission (CEC) in making updates to the California Building Energy Code Compliance Software for Residential buildings (CBECC-Res) to add functionality to simulate the energy performance of heat pump water heaters (HPWHs) with load management capabilities. This report summarizes the work SCE and its contractor team completed to make the necessary enhancements to CBECC-Res. The updates were included CBECC-Res 2019-2.0 which was released on October 6, 2021.[1] The software is now capable of simulating the impacts of unitary HPWHs that are compliant with *Joint Appendix 13 to the California Energy Code (Title 24, Part 6): Qualification Requirements for Heat Pump Water Heater Demand Management Systems* (JA13).[2] The implementation allows software users to explore how HPWHs with load management functionality, that are controlled and operated in accordance with JA13, impact building energy use (kWh) and Time Dependent Valuation of energy and energy costs (TDV kBTU and cTDV$). CBECC-Res now allows load management credit for all residential unitary HPWH water heaters that CEC has certified as compliant with JA13.[3]

Background

On July 8, 2020, the CEC approved JA13 to the California Energy Code (Title 24, Part 6).[4] With the adoption of JA13, designers have the option of using HPWHs with load management capabilities to comply with Title 24, Part 6 when using the performance approach, provided the HPWH systems comply with requirements in JA13.[5]

Although CEC approved JA13, it was not possible to receive credit for JA13 compliant products because the compliance Software (CBECC-Res) did not have the functionality to assign appropriate credit. The CEC requested support from the Investor-Owned Utilities (IOUs) to update the compliance software. This report provides a summary of the project SCE undertook at CEC's request to update CBECC-Res so users could receive credit for using products that comply with JA13.

Project funding was secured in 2020 and the project team began work in September 2020. Enhancements to the 2019 version of CBECC-Res were completed in April 2021 well ahead of the release of CBECC-

[1] http://www.bwilcox.com/BEES/cbecc2019.html.

[2] https://www.energy.ca.gov/filebrowser/download/2261

[3] https://www.energy.ca.gov/rules-and-regulations/building-energy-efficiency/manufacturer-certification-building-equipment/ja13

[4] Supporting documents for the approval of JA13 are available on the Energy Commission's website here: https://www.energy.ca.gov/filebrowser/download/2261.

[5] The Natural Resources Defense Council (NRDC) organized a group of stakeholders who developed the proposed requirement for JA13 and collaborated with the CEC to refine the requirements prior to adoption. The California IOUs participated in the stakeholder group that NRDC organized and was supportive of the CEC's adoption of JA13. The California Statewide Utility Codes and Standards Enhancement (CASE) Team recommended additional revisions to JA13 as part of the 2022 Title 24, Part 6 code development process that were not approved for the 2022 cycle. The Statewide CASE Team's recommended revisions to JA13 can be found in the Single Family Grid Integration and Nonresidential Grid Integration CASE Reports.

Res 2019.2.0 in October 2021. That release contained the full demand response (DR) implementation under the 2019 TDV and ruleset. The project team began work to refine the implementation for the 2022 TDV and software in May 2021 and the revisions were completed in September 2021. At the time of writing, the CEC is testing the latest version 2022 CBECC-Res that includes JA13 implementation. The 2022 software is tentatively scheduled for public release in Spring 2022.

Description of Revisions to Compliance Software

Updates to the software included adding load management capabilities for consumer water heaters that are typically used in single family buildings and when each dwelling unit in multifamily buildings has a dedicated HWPH unit. To add the necessary functionality, the project team made revisions to:

- California Simulation Engine (CSE) [6] – the simulation engine for CBECC-Res;
- HPWH simulation (HPWHsim)[7] – a simulation tool, imbedded in CSE, used to estimate the energy use of heat pump water heaters; and
- CBECC-Res

The updated version of the 2019 software provides credit for JA13-compliant HPWHs (CBECC-Res 2019.2.0). The CEC is also poised to include the JA13 implementation in the forthcoming 2022 compliance software (CBECC-Res 2022).

The project team added the following load shifting modeling capability to CBECC-Res:

- **Basic**: water heater operation is governed by a pre-determined Time-of-Use (TOU) schedule. With Basic, the water heater storage temperature is not allowed to exceed the user setpoint, which has an assumed default value of 125 degrees Fahrenheit (°F) in CBECC-Res.

- **Basic Plus**: water heater operation is governed by a pre-determined TOU schedule (same as Basic). With Basic Plus, the water heater storage temperature is allowed to exceed user setpoint, which has an assumed default value of 125°F in CBECC-Res.

After consultation with the CEC, the team opted not to implement an "Advanced" capability defined below because the CEC was concerned about the ability to verify compliance with the control strategy. The capability requires connection to a utility program, and at the time of compliance verification there is typically no building occupant and therefore no utility customer to opt-in to a program.

- **Advanced**: water heater operation is governed in response to a TDV schedule. This could be implemented using a 24-hour look-ahead strategy or a similar approach to maximize TDV energy / energy cost savings. This implies the water heater is dynamically receiving commands or price signals from outside the home and is responding in a way to maximize grid benefit. Advanced represents the case of maximizing benefit to the grid.

The project team considered implementing load shifting capabilities for central HPWH systems in CBECC-Res but decided not to do so at this time. Central HPWH systems are typically used in multifamily buildings and are all "built-up" and usually custom designs. The CEC, with the IOU's

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[6] https://cse-sim.github.io/cse/index.html.

[7] https://github.com/EcotopeResearch/HPWHsim.

support, is currently developing simulation approaches to estimate the energy performance of central HPWH systems without load management capabilities. Currently, a baseline system without load management capabilities is not well defined in the software so there is not yet a reliable reference for comparison. In addition, there is limited or no data on the design or energy performance of central HPWH systems with load management controls. The absence of empirical data limits the team's ability to develop simulations approaches that can be validated with real-world performance. Although the load management controls that were added to the software for this project could apply to large central HPWHs within CSE, the compliance credit has not been applied to central systems. The project team could explore applying a load management credit for central HPWH systems in the future after baseline systems without load management capabilities are better defined and there is more data on both the practicality of implementing JA13-compliant controls on central HPWH systems and the energy benefits of for central systems. Depending on findings from data collection efforts, it may be appropriate to update JA13 to include technical specifications specifically for central HPWH systems before implementing revisions to the software.

Interpretation of JA13

JA13 defines several control requirements, schedules, and demand management functionality as shown in the excerpt from JA13 in Figure 1 below.

JA13.3.3 Control Requirements

The requirements below are applicable to all control strategies:

(a) **Time-of-use schedules:** The System shall have the capability of storing at a minimum five time-of-use schedule(s) locally, each supporting at a minimum five distinct time periods for both weekdays and weekends, at least three separate seasonal schedules, and daylight savings time changes. The System shall support both local and remote setup, selection, and update of time-of-use schedules. Local and remote setup, selection, and update shall be possible through a user interface (such as an app).

(b) **Demand management functionality**

Upon receiving a demand management price or dispatch signal, the System shall be capable of all the following automatic event responses:

1. **Basic Load Up**: The System will store extra thermal energy without exceeding the user set point temperature. It will avoid use of electric resistance elements unless user needs cannot be met;
2. **Advanced Load Up**: The System stores extra thermal energy, where some or all of the tank may exceed the set point temperature chosen by the user, within safe operating conditions. Advanced Load Up must only be enabled after agreement by the user and utility as defined below. It will avoid use of electric resistance elements unless user needs cannot be met. Advanced Load Up will only be available in Advanced Demand Response Control mode as defined in JA13.3.3.2;

Figure 1: JA13 Excerpt

Source: https://www.energy.ca.gov/media/4122 .

The control requirements in JA13 implies two kinds of schedule regimes and two kinds of tank temperature regimes. For schedules, the water heater will either operate on a fixed, pre-programmed/pre-determined schedule (i.e., TOU-like), or in dynamic way responding to commands sent to the water heater from the electric utility. For temperatures, the tank will either stay at or below the user setpoint, or it will exceed the setpoint. The project team interpreted these regimes to mean that a "Basic" control strategy will use a pre-determined TOU-like schedule and will not exceed the user setpoint.

The compliance software uses TDV schedules instead of actual TOU schedules in simulations. To create an approach that would work with the software framework the project team established pre-determined schedules for Basic control strategy that minimize TDV energy use. The TDV-based schedules used in the simulation are not the same as the TOU schedules that the water heaters will use once installed but the TDV schedules provide a reasonable approximation of benefits to the grid. Developing appropriate schedules was a major component of the project. See Sections 3 and 4 for a discussion of schedules for the 2019 and 2022 software.

For completeness, and to address the 2022 Single Family Grid Integration Team's CASE proposal for the 2022 code cycle,[8] the project team also considered a "Basic Plus" control scenario with static TOU-like schedules but with an increased water heater setpoint above the user default value. It was hypothesized that allowing elevated temperatures could result in TDV reduction benefits beyond what is possible with default temperature setpoints. See the discussion of the Basic Plus analysis in Section 4 for additional information and findings from modifying temperature setpoints.

Due to the associated verification challenges with new construction described above in the introduction, the team did not explore an Advanced Load Up (dynamic) control algorithm for the water heater.

2. Software Enhancements

Implementation of Load Shift Commands at Water Heater Level

Water heaters in the physical world, and in the previous versions of the simulation, are reactive to tank temperature conditions. Tank temperature is monitored, and the water heaters only turn on/off in response to changes in temperature. This control regime had been accurately implemented in the water heater simulation. To model load shifting, the project team needed to restructure the simulation controls to turn a heating component on or off at will. For example, while a water heater may have a typical ten-degree deadband, it was desirable to force the compressor on, inside that deadband, to fully heat up the tank. The command sets presented in Table 1 were added to HPWHsim to enable this functionality. The impact each DRStatus has on the simulation is presented below the table.

Table 1: HPWHsim Load Shift Commands

Integer	DRStatus	Description
0	ON	Normal operation (no special load shift control)
1	LOC	Lock out compressor

[8] https://title24stakeholders.com/measures/cycle-2022/single-family-grid-integration/

2	LOR	Lock out resistance elements
3	LOCLOR	Lock out all heating
4	TOO	Top Off Once
5	TOOLOC	Top Off Once with Resistance Heat only
6	TOOLOR	Top Off Once with Compressor only

Source: CBECC-Res.

Command `ON` (0)– Normal operation

Run as normal.

Command `LOC` (1) – Lock out compressor

Prevents the compressor from running.

Command `LOR` (2)– Lock out resistance elements

Prevents the resistance elements from running

Note: The compressor often uses the lower resistance element as backup. At cold temperatures this command (DR_LOR) can lead to no heat being added to the system when below the compressor lockout temperature.

Command `LOCLOR` (3)– Lock out all heating

Prevents any heating component from running.

Command `TOO` (4)– Top Off Once

Engages the compressor and lower resistance element to start heating the tank to setpoint for a one-time event. This is useful to “charge” up the tank when desired.

This signal engages the compressor and the lowest resistance element in the tank if the heat sources exist. Next the deadband check is completed. If the tank is below the setpoint it will still heat up to setpoint regardless of what the tank temperature.

Note: All packaged HPWH have different deadbands for the different heating elements. There are many cases where the bottom resistive element has a shut off logic below the setpoint (i.e., when the bottom of the tank is 100 °F). In some cases, this command (TOO) may turn on the lower element just to have it shut off and run just the compressor. This is not an issue if running both this command and the LOC command (TOO_LOC) as the compressor will point to the backup resistive element and have it run to setpoint.

Command `TOOLOC` (5)– Top Off Once Lock Out Compressor

Heat the tank to setpoint with resistance elements only.

Command `TOOLOR` (6)– Top Off Once Lock Out Resistance

Heat the tank to setpoint with compressor only.

Note the same issue with cold air temperatures as in Command LOC section, could result in no heating if using this command.

User Interface Updates to CBECC-Res

At the user interface level, it was necessary to add several items including: a list of certified JA13 equipment, an option to select the Demand Response Control type, a way to select the Demand Response control schedule (for research purposes), and a format for that schedule.

Figure 2 presents a view of the drop-down list of several of the certified JA13 water heaters.[9] Figure 3 shows the Demand Response Control Type Selection user interface screen.

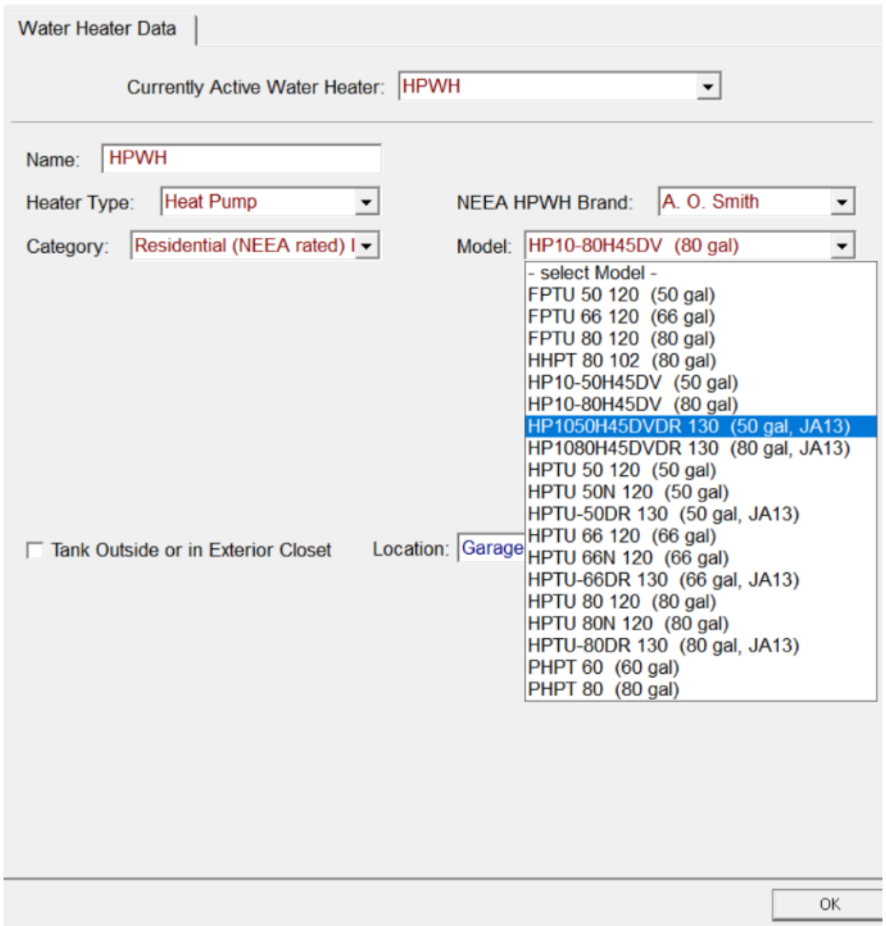


Figure 2: JA13 Certified Water Heaters Drop Down List

Source: CBECC-Res

[9] The full list is available at the CEC site here: https://www.energy.ca.gov/rules-and-regulations/building-energy-efficiency/manufacturer-certification-building-equipment/ja13

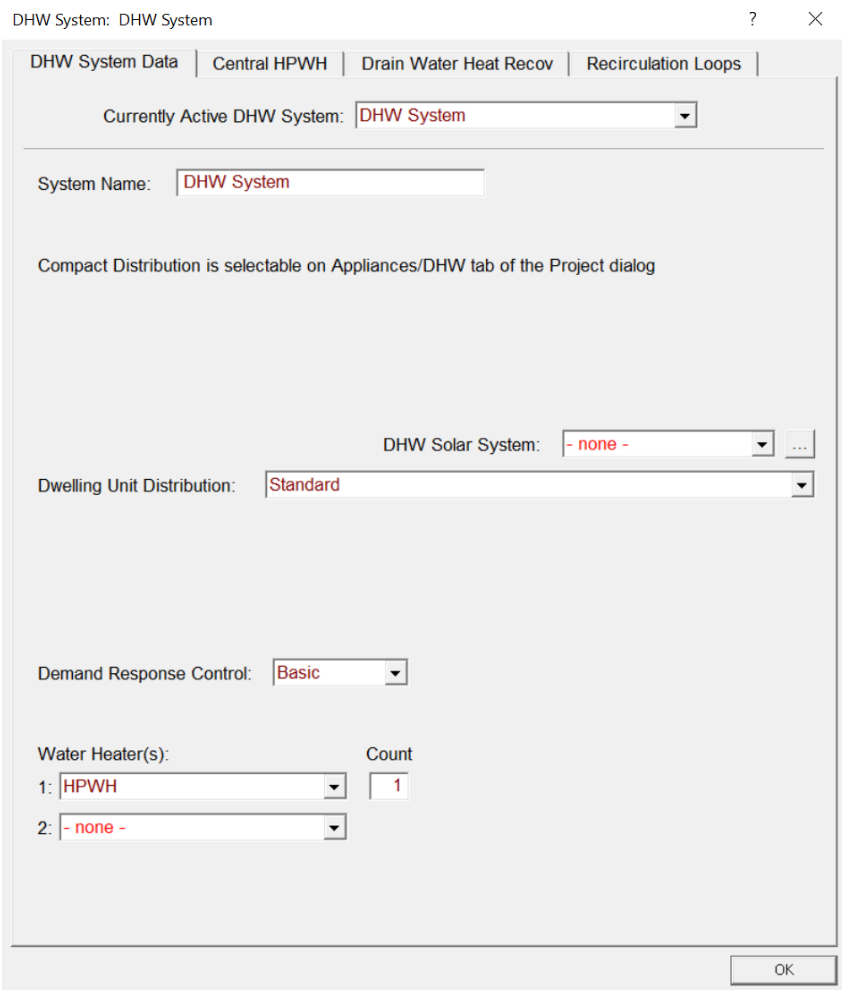


Figure 3: JA13 Demand Response Control Type Selection

Source: CBECC-Res

Schedule Files

Schedule files can be selected for research purposes. For compliance, schedules are fixed based on optimization work described in the next section of this report. To run a different schedule file in CBECC-Res, use the Ruleset Table Replacement feature to swap in a different file for the T24RDemandResponseHPWH_Sched as in Figure 4.

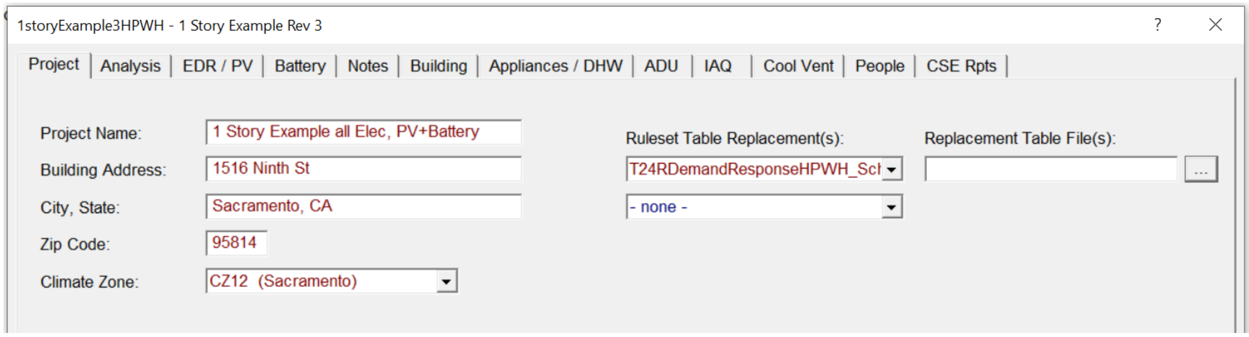


Figure 4: JA13 Schedule File Functionality

Source: CBECC-Res

SCHEDULE FILE FORMAT

An example of the schedule file format is shown below. Each file consists of the following columns, and Table 2 presents an example schedule:

- **Schedule**: a name like “Basic”
- **Climate Zone**: 1-16
- **Month**: 1-12
- **Day Type**: Weekday or Weekend
- **Signal Setpoint**: Signal for specifying a DR command or Setpoint for specifying a Setpoint
- **Value**: There are 24 “Val” columns – one for each hour of the day: Val may be any of the DR Commands if the Signal Setpoint column indicates “Signal” or a tank setpoint in degrees Fahrenheit if the Signal Setpoint column indicates “Setpoint”.

Table 2: Example Schedule

Schedule	Climate Zone	Month	Day Type	Signal Setpoint	Val	…	Val	Val	Val	Val	Val	Val	Val	Val
				Hour=	**1**	**…**	**17**	**18**	**19**	**20**	**21**	**22**	**23**	**24**
Basic	1	1	Weekday	Signal	ON	…	ON	TOO LOR	LOR	LOR	LOR	ON	ON	ON
Basic	1	1	Weekday	Setpoint	125	…	125	125	125	125	125	125	125	125
Basic	1	2	Weekday	Signal	ON	…	ON	TOO LOR	LOR	LOR	LOR	ON	ON	ON
Basic	1	2	Weekday	Setpoint	125	…	125	125	125	125	125	125	125	125
Basic	1	3	Weekday	Signal	ON	…	ON	ON	TOO LOR	LOR	LOR	ON	ON	ON
Basic	1	3	Weekday	Setpoint	125	…	125	125	125	125	125	125	125	125
…	…	…	…	…		…								
Basic	1	1	Weekend	Signal	ON	…	ON	TOO LOR	LOR	LOR	LOR	ON	ON	ON
Basic	1	1	Weekend	Setpoint	125	…	125	125	125	125	125	125	125	125
Basic	1	2	Weekend	Signal	ON	…	ON	ON	ON	ON	ON	ON	ON	ON

Schedule	Climate Zone	Month	Day Type	Signal Setpoint	Val	…	Val	Val	Val	Val	Val	Val	Val	Val
Basic	1	2	Weekend	Setpoint	125	…	125	125	125	125	125	125	125	125
Basic	1	3	Weekend	Signal	ON	…	ON	ON	ON	ON	ON	ON	ON	ON
Basic	1	3	Weekend	Setpoint	125	…	125	125	125	125	125	125	125	125

The schedule file options allow a unique schedule for: each climate zone, each month, weekdays and weekends, and every hour of the day. An 8760 schedule, or schedule that could be unique every hour of a year, is not implemented because these schedules are inspired by TOU rate schedules that do not change at every hour of the year. The project team reviewed TOU schedules across California and found TOU rate schedules typically can have different time of day rates, weekday/weekend rates, and change seasonally (e.g., monthly).

3. Schedule Optimization – 2019 TDV

The project team started defining and optimization schedules for the 2019 TDV. Building off the premise that the static schedules should aim to reduce annual TDV as much as possible, the project team explored more than 20 different schedule possibilities. These ranged from relatively simple to elaborate. Five of the most promising are described below with the project working names provided:

- BasicTOU2
  - Top off tank at 3pm. Lock out resistance 4:00 -7:00 pm every day.
  - Bonus top off at noon.
  - Constant across climates and weekdays/weekends
- BasicTOU2b
  - Like TOU2 but load shift only in months where there are TDV spikes
  - For example, in Climate Zone 9, schedule is only active months 7, 8, and 9
  - Purpose is to avoid unnecessarily running the tank and incurring a penalty. Restated, the baseline operation is often good and hard to improve on.
- BasicTOU5
  - Reduces tank setpoint up to 15 °F during peak periods
    - Evening load up and setpoint reduction at 4:00 pm (months 1-5, 11, and 12) and 5:00 pm (months 6-10) for both weekdays and weekends
    - Morning load up and setpoint reduction at 6:00 am (months 6-10) weekdays
    - Constant across climates
- Thresh1
  - Nuanced control anticipating each climate zone's TDV schedule. Varies by month and weekday/weekend and climate.
- Thresh2
  - Like Thresh1 but requires higher TDV spikes to activate load shift. Therefore, load shifts are less frequent than Thresh1.

An overriding tenet of the load shift exploration is that the DR schedule may not reduce the hot water availability to the occupant. That is, the DR-HPWH is not allowed to provide water below the delivered temperature in the non-load shifted case. If it is found to do so, the schedule is deemed invalid, and the results discarded.

Testing and Findings

The schedules were tested across a suite of parameters including 3- and 4-bedroom prototype houses (to see the effect of different draw schedules), all 16 climate zones, and all six HPWH waters that were JA13 certified at the time of testing.[10]

Testing revealed significant findings including that, because of variations in TDV schedule by climate zone, a single DR schedule produced mixed results across the state. The TDV schedules varied enough that one control schedule may reduce TDV in one climate zone while increasing TDV in another climate zone. Similarly, the second significant finding is that the same schedule provided differing changes in TDV for different HPWH equipment and tank sizes. Even within a given climate zone, some equipment may decrease TDV while others would increase.

These findings led the project team to pursue two courses of action. First, the team realized it would be necessary to allow each climate zone to have a different DR schedule. The best (i.e., lowest TDV) schedule could be shared across some climates but that was not necessarily required. This distinction allows the schedule to be better tailored to the TDV of a certain climate zone. Second, the project team instituted a rule in selecting the optimum schedule that the schedule was the one which reduced TDV the most within one climate for all water heaters while not causing the TDV to increase for any single equipment selected.

Results 2019

Results of the testing and optimization effort are given in the following table for the 4-bedroom prototype. The 3-bedroom results are similar. For each climate zone, the percent change in annual water heating TDV is shown along with the associated schedule that produced the change. The more negative the value, the more TDV savings. The value given is the simple, unweighted average of all six water heaters and is relative to the identical water heater operating without a DR schedule. The schedules listed below and described previously are the ones implemented for the “Basic” load shifting option in CBECC-Res 2019.2.0.

[10] At the time of testing the following six HPWHs were JA13 certified: AO Smith HPTU 50, 66, and 80 gallon; and Rheem ProTerra 50, 65, and 80 gallon.

Table 3: 4-Bedroom Prototype Results (2019 Software)

Climate Zone	Average % Water Heater TDV Change	Schedule Code
1	-7.1	BasicTOU5
2	-4.0	BasicTOU5
3	-6.6	BasicTOU5
4	-2.1	Thresh1
5	-5.6	BasicTOU5
6	-4.9	BasicTOU5
7	-4.2	BasicTOU5
8	-3.4	Thresh2
9	-3.6	Thresh1
10	-2.9	BasicTOU2b
11	-2.8	Thresh1
12	-2.7	Thresh1
13	-3.1	Thresh2
14	-2.8	Thresh1
15	-3.8	BasicTOU2b
16	-7.3	BasicTOU5

4. Schedule Optimization – 2022 TDV

Method Recap – Analogous to 2019

The 2022 TDV schedules are not the same as the 2019 schedules. In general, the 2022 schedules offer more variability and often a distinct drop in TDV midday. The team hypothesized the 2022 TDV would offer more opportunity for decreasing water heating TDV through load shifting.

The team pursued an approach analogous to that used to develop the 2019 schedules to find the greatest TDV reduction for 2022. Again, the team explored over 20 schedules and tested the schedules to see how they performed for different prototypical buildings, climate zones, and water heaters. For the 2022 schedule optimization the project team tested schedules on 1, 2-, 3-, 4-, and 5-bedroom houses. This expanded the number of draw profiles in the test suite relative to the 2019 testing and covered most of the plausible CBECC-Res use cases. As with the 2019 analysis, the project team tested all six HPWH waters that were JA13 certified.

Test Findings and Actions Taken

The extensive test suite for 2022 revealed some of the same findings as in 2019 including differential TDV effects by climate zone and water heater type. It also revealed some more stubborn cases. In all the scenarios explored, there were combinations of climate zone, bedroom count, and HPWH type where no TDV savings could be found. Specifically, using the best performing schedules, of the 480 total combinations of climates (16), bedrooms (5), and water heaters (6), seven cases showed an increase in TDV. Despite numerous changes to the DR schedules, this could not be improved upon.

A detailed investigation of the hourly behavior revealed the cause: TDV super peaks. The water heater simulation, draw patterns, TDV schedule, and DR schedule combine to create a chaotic environment reasonably representative of the chaotic physical world. Each water heater operates over the course of a simulation with a "history." That is, a large draw yesterday can cause the tank to be in a certain state today. If it were only a small draw, the tank would be in a different state because the recovery to setpoint would happen at a different time. Layered on top of this operation is the TDV schedule, which is dominated by super peak events where TDV increases two to three orders of magnitude for several hours. This typically happens in the late afternoon in summer for cooling. If equipment operates on these peaks, it accumulates a large amount of TDV toward the annual total. If it avoids the peak, it avoids the large penalty. We discovered that many of the baseline, non-load shifted water heaters mostly do not operate on the super peaks. Consequently, there is little opportunity for dramatic TDV savings. Conversely, if the load-shifted water heater inadvertently operates for a few hours during a super peak, it can lead to TDV increases.

The graph presented in Figure 5 illustrates the issue with the following explanatory notes:

- TDV Super peak from hour 15 through 19 (blue squares)
- Baseline water heater runs only for a fraction of hour 15 (2:00 pm). (grey line)
- Load shifted water heater runs during hours 15 and 16. It runs because of tank history and draw pattern (DR command set to allow normal operation for these hours). (orange line)
- Total TDV accumulated in hours 15 and 16 = 469
- Total TDV for year = 22,034
- Single 2-hour event accounts for 2% of annual TDV total

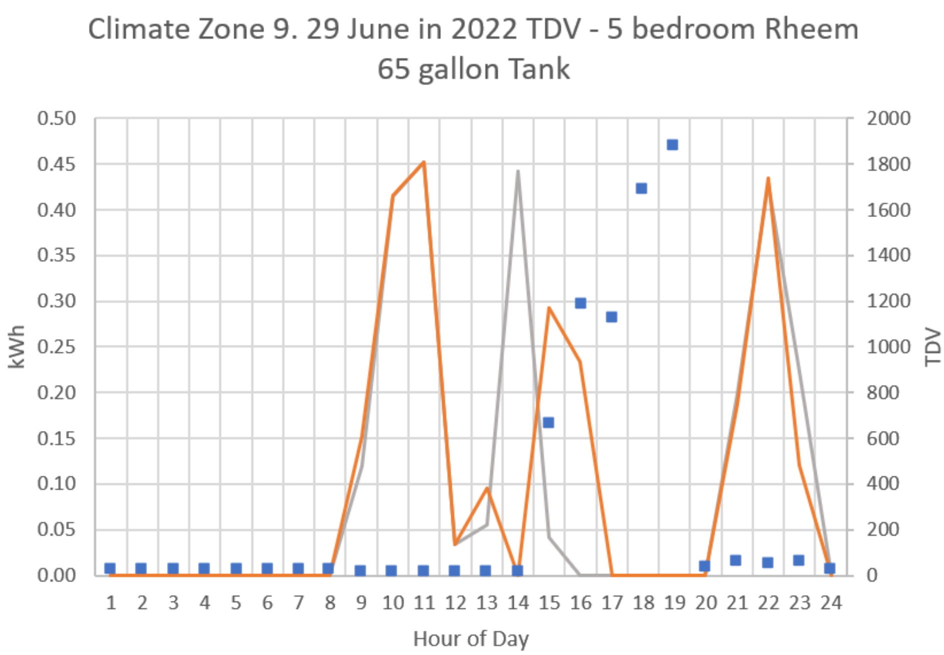


Figure 5: Graph Illustrating Issues with Load Shifting During Super Peak Rates

Water Draw Patterns – Five Shuffle

While there is a fundamental relationship between outdoor temperature and TDV (i.e., hot temperatures lead to cooling use which stresses the grid yielding higher TDV), there is no such linkage between the hot water draw pattern and TDV. This leads to chaotic behavior where the draw pattern causes a collision between super peak TDV and water heater operation. This certainly happens sometimes in the real world, but it was happening as a seeming anomaly in the simulation. Because there are relatively few super peak TDV events over the year, it can only take one or two singular collisions to disturb static load shifting. Yet, there is no basis for this being the case, unlike with space cooling. The solution was to create more water heater draw patterns (5 in total), simulate them all, and average the results. This does a more realistic job of representative typical house behavior and makes the system less chaotic.

The five-draw pattern approach (a "Five-shuffle") was implemented in the development version of CBECC-Res 2022 in May 2021. The 2019 version remained with the single draw schedule. The 2022 version now simulates five unique profiles for each bedroom count and averages the energy and TDV across all five runs for output. One side effect is a slightly longer simulation time, although only the water heating simulation is conducted five times and not the entire building simulation.

The benefit is the system is less chaotic and more predictable. It is more appropriate for determining the value of load shifting and water heater TDV impact overall. Basic load shifting schedules can be found that reduce TDV for all water heaters and bedroom counts within a given climate zone. Note the exception are 50-gallon water heaters in 5-bedroom houses. However, these water heaters are too small to meet the water heating need, according to the California Plumbing Code. Therefore, we do not expect to see this combination installed and do not need to perform the simulation.

Final 2022 Schedules

The schedules yielding the most TDV benefit are described as follows:

- Climate Zones 8-11, 14, and 15: Constant across months. Evening load up at 3:00 pm. Then resistance locked out 4:00 -7:00 pm. Mid-day bonus load up at 12 noon.
- Climate Zones 1-3,5-7, and 12: Lowers tank setpoint at critical periods to 110 °F. Evening load up at either 4:00 pm (months 1-5, 11, and 12) or 5:00 pm (months 6-10). Morning load up ahead of ahead of 7:00 am. Mid-day bonus load up.
- Climate Zone 16: nuanced control varies and changes by the month. Has different weekday and weekend schedule. Requires peak events to be 1.2 times the median TDV for that average day before topping off. Mid-day bonus load up at 12 noon for all months.
- Climate Zones 4 and 13: no schedule months 1-5, 11 and 12. Months 6-10: load up at 3:00 pm, lock out resistance and lower tank setpoint from 4:00 pm-8:00 pm.

Results 2022

The resulting schedules for 2022 TDV are shown in Table 4. A negative value is the percentage change from the baseline of the identical, non-load shifted water heater. As with 2019, the results are the average of all water heaters by climate zone. Individual water heaters vary.

Table 4: 2022 TDV Results

Climate Zone	Percent 2022 TDV Reduction using "5 Shuffle" Draw Profile Approach
1	-6.7%
2	-3.7%
3	-7.6%
4	-4.0%
5	-8.5%
6	-6.8%
7	-8.8%
8	-4.4%
9	-4.4%
10	-4.4%
11	-4.2%
12	-4.7%
13	-8.0%
14	-3.1%
15	-8.2%
16	-22.7%
Average	-6.9%

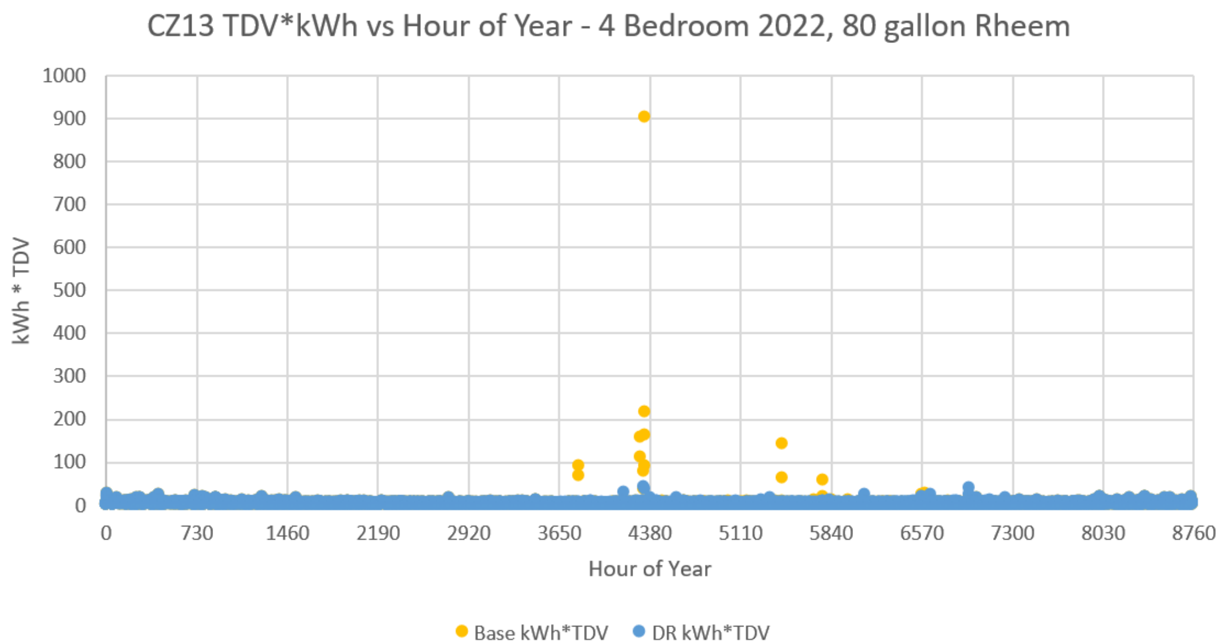
Interpretation

TDV improvements appear to come from the following sources:

1. In the 2022 software version, much of the TDV reduction appears to be coming from locking out resistance heat and lowering setpoint. In other words, being more patient on recovery of tank.
2. Minor benefit of doing tank top off at mid-day. However, mid-day TDV was only ever at most 0.7-0.8 times the median TDV for day. That small differential from the median is not enough opportunity for the water heater to make TDV gains because the load shifted scenarios tended to run the HPWH hotter resulting in more heat loss and lower heat pump efficiency.
3. A few days where we accrue most of the TDV benefits for the entire year (the super peak events).

Two specific examples of how the super peak events can benefit the TDV are described below and illustrated in Figure 6 and Figure 7.

Example one is for a Rheem 80-gallon HPWH in a 4-Bedroom House using the 2022 TDV. "Base" is normal operation. "DR" is load shifted schedule. A large TDV event takes place on June 30th. The Base runs during this period whereas the DR is not running.



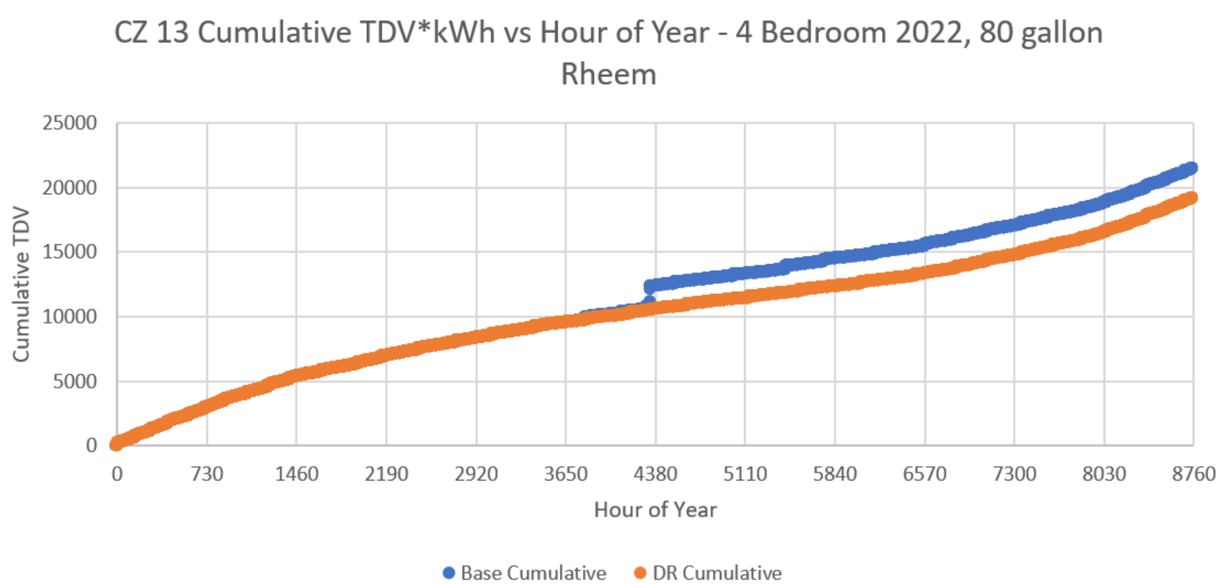
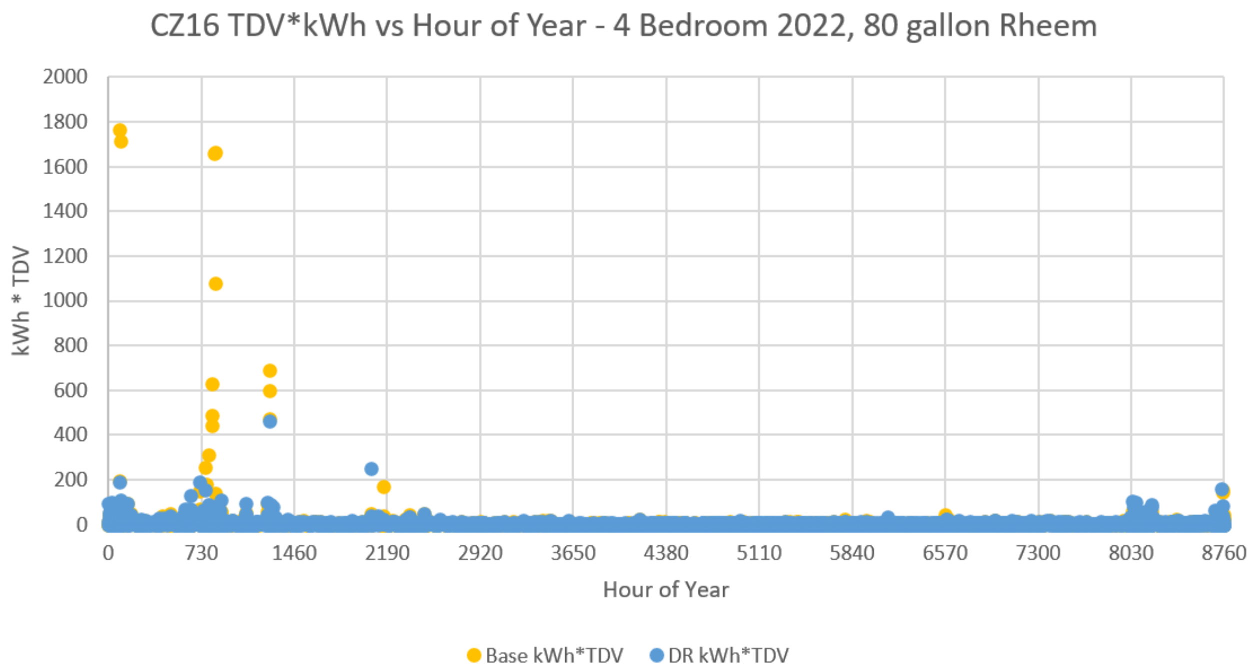


Figure 6: Example 1 of Super Peak Events Benefitting the TDV

Example two is for a Rheem 80-gallon HPWH in a 4-Bedroom House using the 2022 TDV. "Base" is normal operation. "DR" is load shifted schedule. There are big TDV events on January 4, February 3, February 4, February 22. The HPWH runs in Base but not in DR and most of the annual savings from DR operation accrue during these big TDV events.



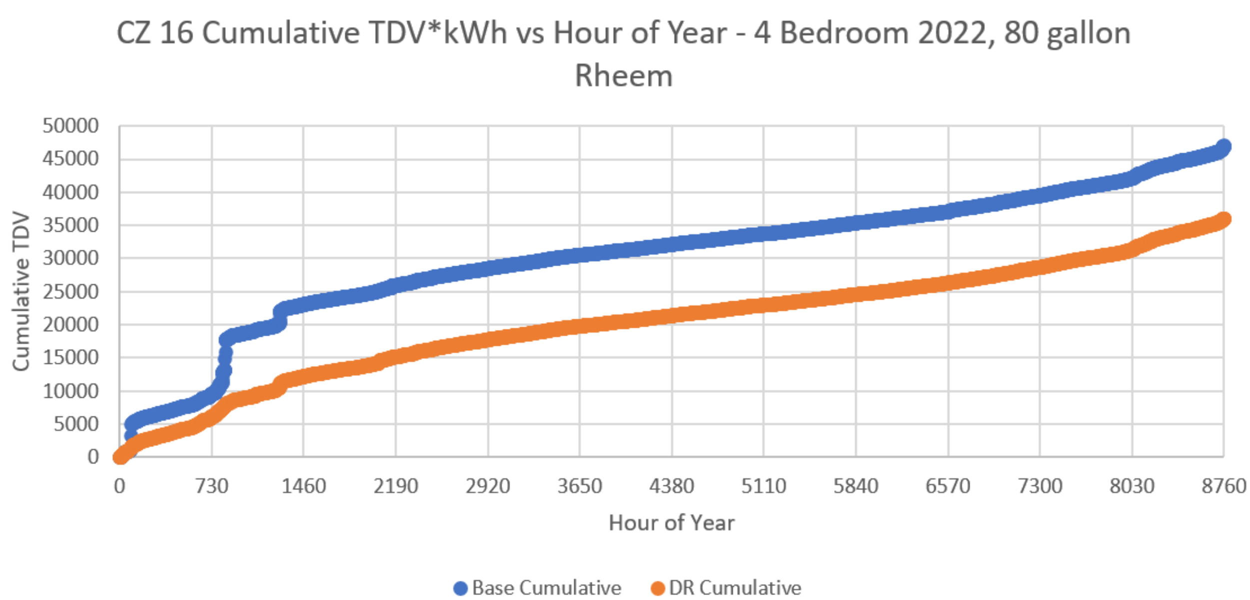


Figure 7: Example 2 of Super Peak Events Benefitting the TDV

Basic Plus

After reviewing the 2022 Single Family Grid Integration CASE report, the project team explored the effect of raising tank temperature on a pre-determined schedule. A mixing valve on the hot water outlet allows for energy level in the tank to effectively increase. Testing was conducted on this approach for both 2019 and 2022; results for 2022 testing are discussed here.

The team started with a set of 16 existing Basic schedules and modified them to increase tank temperature to 130 °F at all load up times identified in those schedules. This typically means a late afternoon load up, noon load up, and, occasionally, morning load-up. Then, the team simulated a 4-bedroom prototype with all 16 Basic-130 schedules and looked for incremental improvement over the load shifted schedules using the default 125 °F setpoint. The simulation suite crossed all climate zones and water heater types. The project team used the 5-shuffle draw pattern approach for the analyses.

Basic Plus Results

The results demonstrated some TDV savings possible with setpoint elevated to 130 °F during load up events compared to load up only to 125 °F. Most climate zones show incremental 1 to 2.5 percent improvement. However, the improvement is not consistent as some water heaters in some climate zones use more TDV. Consequently, we cannot implement any of these schedules in CBECC-Res due to unevenness of results despite there likely being an overall, small benefit. Table 5 shows the results.

Table 5: Basic Plus Results

Climate Zone	Schedule Name	% TDV Reduction Over 2022 Basic DR Control	Savings for all HPWHs in CZ?
1	22BasicTOU5b^130	-1.2	Yes
2	22BasicTOU2^130	-1.3	**No**
3	22BasicTOU5b^130	0.3	**No**
4	22BasicTOU2^130	-2.4	Yes
5	22BasicTOU5b^130	-1.4	Yes
6	22BasicTOU2^130	-1.6	**No**
7	22BasicTOU5b^130	0.0	**No**
8	22BasicTOU2^130	-1.4	**No**
9	22BasicTOU2^130	-1.4	Yes
10	22BasicTOU2^130	-2.3	Yes
11	22BasicTOU2^130	-2.7	Yes
12	22BasicTOU2^130	-1.6	**No**
13	22BasicTOU2^130	-1.8	Yes
14	22BasicTOU2^130	-2.4	Yes
15	22BasicTOU2^130	-1.8	**No**
16	22thresh1b^130	-0.4	**No**
	Average	-1.5	

Further schedules, with higher setpoints to 135 °F were not explored. Results are highly unlikely to improve as higher setpoint if 130 °F is already marginal. The problem is not lack of ability to store energy in the water heater, it is more fundamental in that the arbitrage opportunity of TDV schedule and water heating energy is not large enough at current TDV schedules and equipment efficiencies.

5. Conclusions and Takeaways

Conclusions

The project delivered basic load shifting capability for HPWHs per JA13 guidelines for both 2019 and 2022 CBECC-Res. Below is a summary of key conclusions and takeaways from this project:

- Demand response with HPWHs can effectively reduce TDV (but usually increases annual energy).
    - More variability in the underlying signal (TDV) offers more opportunity
- 2022 Basic load shift control offers more TDV reduction than in 2019.
- The increment of TDV reduction for the elevated setpoint to 130 °F in 2022 is modest and not uniformly beneficial for all HPWHs modeled.
- Software (and TDV) successfully creates a chaotic and representative, realistic environment in which to test water heater demand response.
    - Results are often unpredictable given how many layers and calculations are involved. Linear models or regression curve fits do not appropriately capture the behavior of this technology.
- Hot water draw schedules, in the real world, are variable house-to-house and within houses for a given day. There is not a strong correlation, or even expected causal link between water use and TDV.
- Further TDV reductions may be available in the future with a dynamic, advanced DR algorithm or more dynamic TDV schedules (in 2025).

Next Steps / Future Work

Possible future work and next steps to further advance the cause of enabling and studying load shifting for unitary HPWHs include:

- **Creating an advanced algorithm.** Before implementing in CBECC-Res for new construction, it would be important to determine how the JA13 credit would be verified. Aside from new construction, having an advanced algorithm could be useful as a research tool to demonstrate the capability and value of load shifting HPWHs in the existing housing population as residence join a utility program for load shifting water heating. This capability could be used to estimate benefits and costs for such a program.

- **Enabling central system load shifting capability.** Completing this task will require defining a number of unknowns, or currently ambiguous system descriptions, in the baseline. Particularly the storage volume size would need to be known, and the default controls are for a given system. Because central systems are currently all "built-up" and custom designed per project, the usefulness of a defined standard is limited. A reference system design, or multiple references that are well defined is needed to move forward with this effort.

- **Methodology to simultaneously update TDV and control schedules.** Looking ahead to 2025 and future code cycles, for any changes in the TDV schedule, a new pre-determined schedule needs to be devised. A change to the TDV schedule, without a change to the control schedule could inadvertently result in increasing annual TDV under load shifting. On the other hand, a new TDV offers a new opportunity to find more load shifting savings.

- **Exploring benefits of increased tank size.** The current load shifting credit is given assuming the same tank size used in the reference case and proposed case. It could be useful to compare different (larger) tank sizes in the proposed case. Upsized tanks allow for more energy storage capacity.