Summary of DSO+T Study Water Heater Modeling Issue

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The Transactive Systems Program is conducting an analysis of future distribution system operators using a transactive approach to engaging large fleets of distributed energy resources (DERs; batteries, EVs, PV inverters) and flexible loads (hot water and heating/cooling) in grid operations to help meet DSO objectives, and participate in wholesale markets, at a regional scale resembling the ERCOT footprint (the "DSO+T" analysis). In preparing the simulation that is foundational to the DSO+T project, the thermal model of water heaters included in GridLAB-D was found to be unsuitable for the planned analysis. This model is used for two essential purposes in such studies:

1. **Base Case Water Heater Loads.** Represent a diverse population of thousands to hundreds of thousands of instances of individual water heaters are modeled to establish the baseline water heater class load in the base case scenario.
2. **Dynamic Flexibility of Water Heater Loads.** The same population is modeled with transactive agents controlling the water heaters so as to respond to attractive opportunities to displace customer electricity costs, while minimizing any loss of hot water service to the customer.

Background. Modeling of water heater loads for analysis of such "building-to-power grid" applications has significantly different needs than traditional modeling of a water heater designs for development of efficiency standards or technology. Design modeling requires only one or a few patterns of hot water use, so only a single tank is analyzed, repeating the exercise as necessary to understand the effect of various boundary conditions (principally hot water use) on energy consumption and efficiency, and then to explore design options. Such a process affords highly detailed models of the physics of a water heater, many vertical nodes or even a full 1- or 2-dimensional fluid dynamic simulation of temperature stratification in the water heater interacting with the (typically) two thermostatically-controlled heating elements, one near the bottom and the other 2/3 of the way to the top of the tank. The computational efficiency of such simulation models is not an issue when modeling a few cases.

For grid analysis purposes, modeling the load that results from large populations of water heaters presents the challenge of requiring a much more computationally efficient strategy. One reason large numbers of water heaters must be modeled for grid analysis is that the results must represent the result of latitudinal variation in water heater age, efficiency, and customer usage patterns, as well as longitudinal variations over time that capture diurnal, weekly, and annual usage patterns.

The need for computational efficiency in grid analyses is greatly exacerbated by the physical interactions of end-use devices with the grid. There are both behavioral and physical interactions that are significant.

A key characteristic of dynamically-flexible end-use loads with respect to the power grid is that the sum of populations of loads does not look like the individual loads. Individual time series for loads like water heaters look like individual square-wave impulses of various widths, (in residential populations) each with a nominal power level of 4.5 kW (see voltage discussion below). The timing and duration of these impulses primarily represent the hot water usage pattern which, unlike standard water draw cycles assumed in design models, vary in quasi-random way around a probability distribution of hot water use as a function of time of day and day of week. When such pulsed load patterns are summed or averaged, either latidudinally across a population or longitudinally across time, the result is an end-use load shape familiar to grid analysts that represents the central tendency of the population's diversity across time and space (e.g., individual customers).

The effect on loads like water heaters of dynamically interacting with the power grid via prices, incentives, or other signals is that doing so tends to disrupt their natural load diversity, which then returns gradually to its natural level after some period of time. This occurs because when such a signal is suddenly received that, for example, causes many or most water heaters to avoid heating, they build up a deferred load as the hot water in their tanks is depleted. When release to normal operation, they are suddenly entirely synchronized: they all run flat out at full power until they restore normal operating conditions (temperatures in their tanks). This is why there is a strong "rebound" effect after such events, during which loads are <u>much</u> higher than ever seen in the base case (and one of many important reasons why more sophisticated dispatch of flexible loads, such as transactive approaches, are needed). Since the duration of the restoration period depends on the initial state of the water heater temperatures, their physical characteristics, and subsequent hot water usage, the restoration times vary and their combined loads begin to re-diversify thereafter.

Further, nearly all end use loads, including water heater's resistive heating elements, physically interact with the grid voltage (and, to a lesser extent, frequency and local power factor). Unlike a design exercise, where voltage is simply assumed to be constant at the nominal service voltage (e.g., 240-V), and in fact is not usually even included as a model input parameter, grid voltage varies continually and spatially, directly affecting the power consumption proportionally. Co-simulation techniques that are foundational to GridLAB-D, FNCS, and HELICS resolve this issue by iteration between the power flow solution and the load solution, requiring convergence on the voltage at end-use nodes such as water heaters at each time step.

For all the above reasons, large numbers of water heaters must be modeled simultaneously and iteratively when modeling the power grid. So, the computational burden of modeling water heater loads (and end-use loads generally) is immense, and the solution efficiency of each model component from power flow to DERs to end-use loads is critical to making such simulations practical. Further, the exact characteristics of any given water heater are not at issue (from the grid perspective), rather the mean values for those characteristics and distributions around them are what is important. So, some compromise in the fidelity of the physical model of the water heater model (or models of any end use load) is acceptable for the sake of computational efficiency if the water heater model captures the fundamental behavioral and functional characteristics (including a proper heat balance), within reasonable limits.

Problem Discovered with GridLAB-D's Water Heater Model. The simplified model of water heaters used by GridLAB-D captures the effect of cold water entering the tank at the bottom immediately triggering the heating element to turn on. It represents the depletion of the hot water as a displacement of some fraction of the uniformly hot water in the tank by uniformly cold water entering the bottom. It makes the simplifying assumption that there is no mixing between them. It subsequently keeps track of the movement of the boundary between two layers (the "thermocline"). When some cold water is in the tank, tank jacket heat losses are subtracted from it by moving the thermocline downward. The power remains on until the thermocline reaches the bottom of the tank (at which point losses are represented by temperature decline in the upper layer of the tank. The heat added reduces the thermocline until it reaches the top f the tank. The heat remains on to make up for any temperature drop due to losses, until the setpoint is reached. If no water is used, the heat losses are simply reflected by a slowly declining temperature in a fully-mixed tank. The complication of modeling the control of the two heating elements (only one can operate at a time, with the upper having priority) is largely avoided. This is a simple model of water heater loads that is computationally efficient and reasonably accurate for modeling base-case loads, where setpoints are assumed to remain constant.

However, there is a problem with this model when a sophisticated grid-responsive control (like a transactive agent) is added to the water heater that responds by adjusting the upper and/or lower heating element temperature setpoints (rather than simply turning the power to the tank off). Imagine the water heater model described above receiving an instruction from its supervisory control (e.g., transactive) layer to lower the setpoint temperature from 130°F to 120°F in response to suddenly higher prices. A hot water draw displaces hot water in the tank with cold, represented by the thermocline rising. The heating element, whose thermostat is in contact with the cold water, turns on. It gradually reduces the thermocline to zero when, voila … the tank is now (magically) at 130°F! The tank continues to heat the water below the thermocline to the temperature of the water above the thermocline, despite the setpoint, because of an inherently flawed but hidden assumption in the model. (The tank temperature gradually declines due to jacket heat losses when the thermocline position is at the top of the tank, but very slowly over a period of days unless a very large water draw occurs that drains the entire tank, e.g., the thermocline moves to zero and <u>then</u> is restored to the new setpoint.

In addition, the DSO+T analysis design strongly urges the application if a mixing valve to each water heater to dramatically increase its flexibility without commensurate impacts on the user. A thermal mixing valve automatically mixes cold water with the hot water supplied from the tank to maintain the temperature of the hot water delivered to the user at a temperature equal to (or less, if the hot water tank is depleted) below the mixing valve's setpoint temperature. This allows the water in the tank to be preheated during low price (e.g., nighttime) hours to much higher temperatures than normal (e.g., 160°F), without risk of scalding, allowing it to "coast" for much longer periods before requiring heat to be added to maintain a temperature that has been reduced to normal (e.g., 130°F).

The current GridLAB-D model of water heaters does not include a mixing valve.

How the temperature setback problem can be quickly remedied for the DSO+T analysis is under investigation. The mixing valve feature will be added during this process. PNNL is looking at two potential models that would more accurately represent the situation of a temperature setback in water heaters, while maintaining a degree of computational simplicity. The first is to stack two of the current "moving thermocline" models in series, allowing <u>two</u> (but only two) thermoclines to be tracked, separately representing the upper and lower heating element setpoints, and allowing a single change back and forth from a higher temperature to a lower temperature. (This would still not be able to model continuously variable thermostat setpoints, the general case, which is a highly desirable property for such simulations.)

The other approach is simply to model the tank as two-fully mixed, fixed volume layers, one at the bottom and the second above the upper heating element. Such models allow multiple, arbitrary temperature setpoint changes. It is worth noting that the addition of a mixing valve makes nodal solutions highly non-linear, requiring approximate (e.g., finite difference) solutions at fine grained temporal resolution, slowing down the calculations.

These types of models can have an arbitrary number of nodes and can assume to have no mixing between layers, or a mixing coefficient can be assigned to represent the convective and conductive heat flows from lower, cooler section to the upper section. How such mixing coefficients should be calibrated to physical constants, or more detailed, physically accurate models that mix both the thermocline and convection/conduction effects in one and two-dimensions interact with the one-dimensional slug flow of the water draws.

Alternative modeling approaches could prove even more general and more accurate. One example is the possibility of a multi-layered, moving ("floating") thermocline model.

Testing such models against empirical data could reveal which models are best suited, how accurate they are, and under what circumstances.

This, and/or the development of more suitable models, is beyond the scope of the DSO+T study and is left as a subject for further research on more suitable models. The water heater issues described above are illustrative of the kinds of modeling capabilities for end uses that, while well established for design/efficiency studies, have not been explored or resolved for the increasingly important studies where the dynamic controls inherent in building-to-grid applications are paramount.