Flexible Load Conformance

A Work-in-Progress White Paper

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Acronyms

AHRI	Air-Conditioning, Heating, & Refrigeration Institute
CoP	Coefficient of Performance
CTA-2045	ANSI/CTA-2045-B
DFWH	demand flexible water heater
DLC	direct load control
DR	demand response
ERWH	electric resistance water heater
HPWH	heat pump water heater
LME	load managing entity
NEEA	Northwest Energy Efficiency Alliance
OEM	original equipment manufacturer
PSU	Portland State University
SGD	smart grid device
UCM	universal communications module
WH	water heater

Glossary

Advanced Load Up Energy Take A *CommodityRead* reply, *Commodity Code* 11: *Advanced Load Up* Present *Energy Take*, *aka Advanced Load Up Present Energy Storage*. The amount of electrical energy that the smart grid device can consumer at the moment of the *CommodityRead* request when considering the extra capacity for *Advanced Load Up*.

Advanced Load Up Intermediate DR application request. The smart grid device stores extra thermal energy in excess of the customer set point though within safe operating conditions.

CommodityRead A Basic DR application request used to exchange information regarding the smart grid device consumption.

Compliance A determination as to whether a smart grid device understands and responds appropriately to defined protocol messaging.

Conformance A determination as to whether a smart grid device performs in response to messaging in a manner that benefits both the load managing entity and the device owner.

Critical Peak Event A Basic DR application request wherein a smart grid device is requested to reduce energy consumption more than a *Shed* request. The reduction would likely affect the comfort of the owner.

Energy Take A *CommodityRead* reply, *Commodity Code* 7: Present *Energy Take*, *aka Present Energy Storage*. The amount of electrical energy that the smart grid device can consume at the moment of the *CommodityRead* request.

Flexible Load Management The coordinated dispatch of large aggregations of flexible loads and other smart grid devices to provide utility grid services.

Grid Emergency A basic DR application request wherein a smart grid device is requested to reduce energy consumption more than a *Critical Peak Event* request. The reduction is very likely to affect the comfort of the owner.

Grid Service Grid services are the means to achieve electrical grid operational objectives, which are *"the fundamental underlying physical needs . . . of the grid for safe, reliable, robust, and economically efficient operation."*

Load Up A basic DR application request that the smart grid device run upon receipt of the request and operate until the maximum stored energy state is reached.

Normal An operating state wherein no demand response event is in effect. The smart grid device may be in an Idle Normal state (no or insignificant energy consumption), or a Running Normal state (significant energy consumption)

Price Stream Communication Provides means for communicating time and price data to an smart grid device, enabling price-responsive consumption.

Shed A Basic DR application request wherein a smart grid device is requested to reduce energy consumption. The reduction should not affect the comfort of the owner.

1 Introduction

Utilities have used residential loads for providing grid services to utility customers for decades, particularly demand response (DR) (Hastings 1980; Kolln et al. 2023; Pratt et al. 2021; Stitt 1985). However, the number of customers participating in such programs remains low. Multiple reasons contribute to this lack of growth in DR programs (Parrish et al. 2020). Two of these reasons are negative customer experiences and immature interoperability.

New *Flexible Load Management* strategies for providing grid services have the potential to accelerate customer participation. Such strategies consider customer experiences and maximize interoperability. Customer experiences are impacted by loss of agency over customer-owned appliances, concerns regarding privacy of information, and insufficient or poorly-associated incentives. Interoperability is "the ability of two or more systems or components to exchange information and to use the information that has been exchanged (ISO 2017)." Mature interoperability decreases systems integration costs and reduces participation barriers for customers (Knight 2020). Improving customer experience and interoperability thereby increases the load balancing capacity of DR programs to the benefit of both customers and electric utilities.

A key principle of this document is that utility grid services should never be a concern of flexible load manufacturers. Original equipment manufacturers (OEMs) need not have to consider how their products can best support grid services; their product design requirements should not depend on how a utility defines its peak demand program nor how it manages its event remediation schema. The huge number of utilities and all their various grid serves would confound the design space. Rather, OEMs need only consider how their products behave in response to ANSI/CTA-2045-B messaging. Considering the grid services stack in

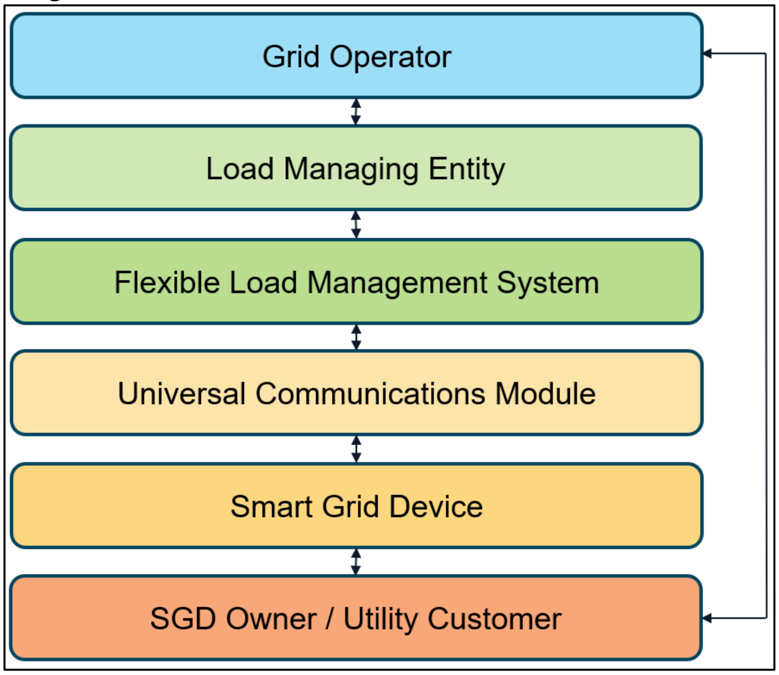

Figure 1, OEMs' flexible load products need only be concerned with messaging between the universal communications module and their customers.

To that end, Portland State University's Maseeh College of Engineering & Computer Science Department of Electrical & Computer Engineering conducted the research described in this paper.

1.1 ANSI/CTA-2045-B

ANSI/CTA-2045-B (herein *CTA-2045*) is a modular communications interface standard that enables a load managing entity (LME) to integrate customer-owned flexible loads into grid service programs (CTA 2020). Flexible loads are referred to as smart grid devices (SGDs) within the standard. The standard specifies a physical module interface, known as the universal communications module (UCM), as well as a protocol that defines communications methods and attributes. The module interface, *aka* the branded name EcoPort™, enables SGDs from a wide variety of OEMs to integrate into any type of grid service program, provided the SGDs and UCMs comply with the protocol requirements. This mature level of interoperability enables the standard to be compatible with any type of *Flexible Load Management* program, whether it be direct load control, service-oriented, real-time price-based, or any other.

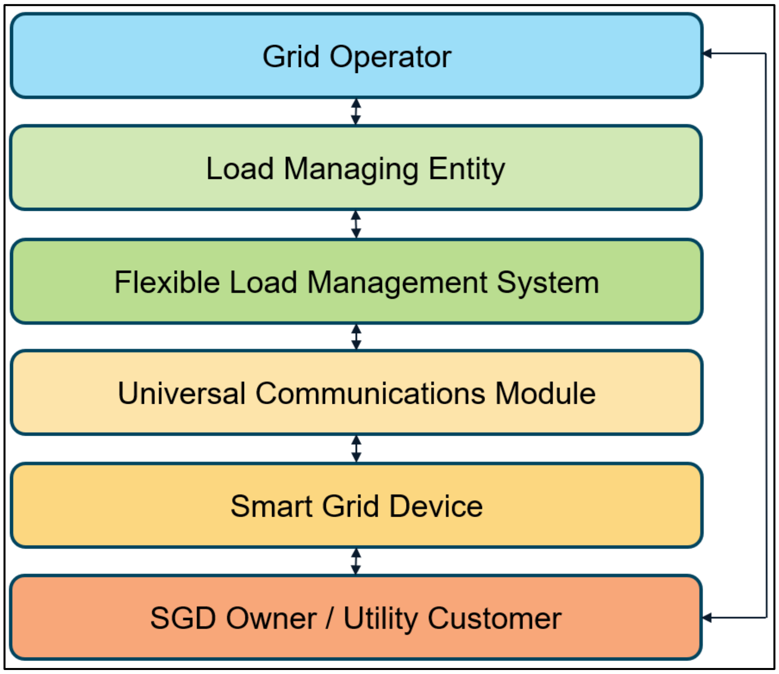

Figure 1. The *Flexible Load Management* Stack
Shows the communication pathways between various actors within a flexible load management system. The stack abstracts interface responsibilities among the actors, showing that their interactions shall be limited to adjacent actors. Grid operators requisition grid services from LMEs, who use their flexible load management systems to exchange information with UCMs. OEMs need only concern themselves with messaging between the SGD and the UCM, as well as their customers' relationship with their products.

The CTA-2045 standard addresses customer privacy concerns by limiting information exchange of customers' SGDs to a minimal list of attributes. The standard also addresses customer agency concerns; CTA-2045 works on the principle that it is not the responsibility of the LME to tell an SGD how to behave in response to a message. Rather, it is the responsibility of the SGD OEM to program the SGD to act on each request in a way that is appropriate for that specific SGD while being considerate of customer comfort during deployment. A well-designed response will concurrently provide effective grid service participation while minding the needs of the SGD owner.

1.2 Compliance and Conformance

For grid service programs to be effective, SGDs must understand and respond appropriately to protocol messaging, which is referred to as Compliance. In addition to needing to comply with protocol messaging, SGDs must also behave in response to messaging in ways that make them useful grid service participants. This behavior is referred to as Conformance. Compliance pertains solely to messaging; does the SGD meet the requirements of the communications protocol? Conformance pertains to how the SGD behaves in response to messaging; does the SGD conform to expectations of a useful program asset? While compliance validates messaging required by the protocol, conformance focuses on aligning SGD behavior with utility and customer expectations. Compliance alone does not guarantee a useful program asset. Only SGDs that are conformant can provide utilities with capacities and capabilities that contribute to successful delivery of grid services.

SGDs from different OEMs do behave differently when an identical CTA-2045 message is sent to the units. For example, a water heater from one OEM may act on a CTA-2045 *Shed* command request by lowering its internal set point by 3°F, while a water heater from another OEM may act on a *Shed* command request by widening its deadband by 10°F. The discrepancy of responses has implications for demand response programs and customer comfort. Conformance testing helps to identify which SGDs perform in a manner that is beneficial to both utilities and consumers.

Within CTA-2045, the lack of descriptive SGD behavior in response to messaging was intentional, with the idea being that OEMs should have flexibility in designing how their grid-enabled products respond to messaging requests. This allows the OEM to protect the integrity of its equipment, meet customer needs, and protect its brand.

There are times when the behavior of an SGD as defined by the OEM may not actually contribute to a grid service or may burden the SGD owner with poor performance, despite unit compliance with CTA-2045. These are issues of conformance.

Therein lie multiple gaps in expectations between LMEs, OEMs, and SGD owners. LMEs expect OEMs to produce SGDs that provide meaningful contributions to grid services, and they expect their customers to want to purchase those SGDs. OEMs expect to keep their customers satisfied with excellent reputational service that will not become tarnished and equipment that will not become damaged due to grid service participation. And, they expect to attract attention from LMEs for SGD purchase recommendations or incentives. Appliance owners expect OEMs to offer SGDs that do not compromise agency over their SGDs, and they expect their LME to operate grid service programs that do not compromise their privacy. They also expect both the OEMs and their LME to provide excellent service.

1.3 Smart Grid Device Testing Basics

To perform compliance and conformance testing of CTA-2045-enabled SGDs, a UCM is attached to the unit EcoPort™, which enables messaging between the SGD and the test operator. Once grid-enabled, a *Commodity Read* response is sent from the UCM to the test operator. *Commodity Read* is the list of required parameters as per the CTA-2045 standard. These parameters include *Operation State, Present Energy Take*, *Total Energy Take Capacity,* and *Electricity Consumed (Watts).*

Temperature varies within water heaters (WHs) due to tank stratification, a natural phenomenon whereby water separates into layers. Water density decreases with increasing temperature, so water will stratify into cold layers at the bottom of the tank and warm layers at the top. Depending on how an OEM calculates the measured tank temperature, it is possible that the upper part of the tank is hotter than the reported temperature. An accurate representation of tank temperature will have some minor variations between the top and middle sections of the WH tank (Clarke 2018).

Smart grid devices use protocols, such as CTA-2045, to standardize communication between electric utilities and customer-owned assets. CTA-2045 messages include *Load Up* and *Advanced Load Up* (requests to consume energy), as well as a series of messages with increasing amounts of energy consumption deferral: *Shed* (a light deferment request), *Critical Peak Event* (a deep deferment request), and *Grid Emergency* (a full deferment request).

However, water heater behavior following successful communication is defined by OEMs. The CTA-2045 protocol does not indicate how an SGD must respond in accordance with the protocol. The onus is on the OEMs to determine SGD behavior. As a result, this creates diversity of behaviors in response to basic message requests.

Variations in behavior within aggregations of SGDs may lead to inconsistency in grid service capabilities, making it difficult for electric utilities to plan and deploy grid services. In turn, this could negatively impact power system reliability, degrade customer satisfaction, and ultimately decrease customer enrollment in grid service programs. The benefit of undefined SGD behavior opens the door to creative solutions by OEMs, which must balance the need to protect their brand by providing service to their customers, while also providing LMEs with effective load shifting capabilities. OEMs can be expected to have an excellent understanding of the needs of their customers. This document aims to provide OEMs with better awareness of how LMEs can use their SGD products to support flexible load management programs. Subsequently, this may create competition between OEMs to design better products that have greater appeal to both customers and LMEs.

1.4 Fundamentals of Energy Take

Present Energy Take, *aka Present Energy* or herein just *Energy Take*, is an estimated value. It represents the amount of electrical energy that would be consumed by an SGD to complete a task. In the case of a water heater, *Energy Take* is the amount of electrical energy that would be consumed to bring the tank water temperature to the set point temperature. Most 40- and 50-gallon WHs have upper and lower temperature sensors. One method for calculating the *Energy Take* of an electric resistance water heater (ERWH) is to use weighted values from the two temperature sensors, T_{lower} and T_{upper}, to calculate a single representative tank temperature, T_{tank}, Equation 1, which is then used to calculate *Energy Take*, Equation 2.

$$T_{tank} = AT_{lower} + BT_{upper} \qquad {}^oF \qquad (1)$$

$$EnergyTake_{ERWH} = (0.2930)(V_{tank})(8.249)(T_{set} - T_{tank}) \qquad Wh \qquad (2)$$

A and *B* are weighting coefficients that account for thermal stratification within the tank, with $A + B = 1$. Temperature units are in °F. 0.2930 Wh/lbF is the specific heat of water, V_{tank} is the tank volume in gallons,[1] and 8.249 lbm/gal is the temperature-dependent density of air-free water at 120°F.[2]

Equation 2 assumes that all of the electrical energy drawn by the ERWH is converted to thermal energy, which is pretty much true. However, this equation cannot be used to calculate the *Energy Take* of heat pump water heaters (HPWHs). Calculating the *Energy Take* of HPWHs requires consideration of the Coefficient of Performance (CoP) of the heat pump, as shown in Equation 3.

$$EnergyTake_{HPWH} = \frac{1}{CoP}(0.2930)(V_{tank})(8.249)(T_{set} - T_{tank}) \qquad Wh \qquad (3)$$

CoP is the sum of the thermal energy transferred to the tank, *Q*, and the amount of electrical energy consumed in transferring that thermal energy, *E,* divided by that electrical energy. The amount of transferred thermal energy is a function of the ambient temperature outside the HPWH and the water temperature inside the HPWH. CoP decreases as the tank temperature rises; it is not a constant value.

$$CoP_{heating} = \frac{Q+E}{E} \qquad unitless \qquad (4)$$

Reiterating, *Energy Take* is an estimate of the amount of electrical energy that would be consumed by a water heater in raising the temperature of stored water to a set point temperature. The equations presented in this section are insufficient for describing the heat transfer, fluid mechanic, and thermodynamic behaviors of heat pump and electric resistance water heaters. *Energy Take* values are affected by the thermal lag of convective heat transfer, the number of temperature sensing points, temperature sensor calibration, compressor motor power factor, and the temperature dependence of CoP, among many other variables. As such, expectations of *Energy Take* precision must be tempered when considering the value of this datum.

[1] Actual V_{tank} is often lower than the nameplate V_{tank}; e.g., 46 gal instead of 50 gal.

[2] The temperature-dependent density of air-free water is calculated using the empirical formula $\rho = (999.85 + 6.326x10^{-2}T - 8.523x10^{-3}T^2 + 6.943x10^{-5}T^3 - 3.821x10^{-7}T^4)$ kg/m^3, with T in °C.

2 Observed Conformance Issues

This section presents several cases of appliance behaviors in response to CTA-2045 messaging that the authors deem to be non-conformant with the expectations for SGDs. Unlike compliance responses, which are defined by protocol requirements, conformance behaviors are not defined by a standard and are therefore subjective. However, some guidance has been provided by AHRI 1430-2022 and California Title 24 JA 13, as discussed in Section 3.

One may describe conformance issues as behaviors that do not meet the expectations of customers or LMEs. For example, customers expect hot water when needed. Ideally, customers should not be aware that grid services are occurring. SGDs that avoid discomforting customers would help improve customer enrollment numbers in flexible load management programs. As another example, an LME should expect SGDs to provide reliable and reasonably accurate *Energy Take* values, which would allow the LME to better plan grid-services.

These cases are presented to illustrate how CTA-2045-enabled appliances have been observed to behave under test conditions and to start discussions about how they should behave as customer-friendly SGDs.

2.1 Miscalculation of Energy Take

Figure 2 shows the response of two ERWHs to a *Load Up* message following a *Shed* event. These units have identical water capacities and power ratings, and similar geometries. Prior to the *Load Up* request, the units are in *Shed* mode and their *Energy Take* values are high. After the *Load Up* request is made, the heating elements turn on and the powers increase to around 4.5 kW (red). Typically, the upper tank element turns on first, then the lower tank element turns on. Both elements are never on concurrentlty.

The plot on the left shows an expected response. As soon as the upper heating element turns on, the *Energy Take* begins to decrease. After the lower element turns off, the consumed energy (area under the power curve) nearly equals the *Energy Take* at the beginning of the *Load Up* period; there is a 9% difference between the two values.

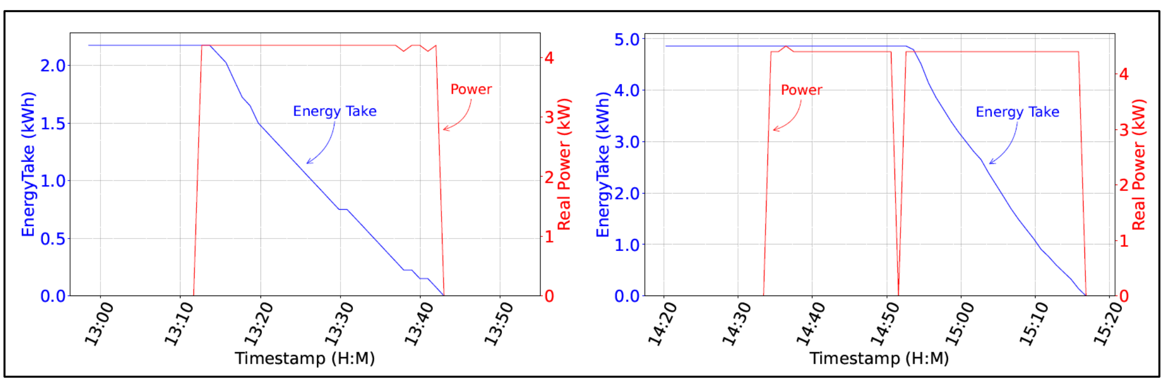

Figure 2. Observations of *Load Up* behaviors and *Energy Take* calculations
Left plot: Proper calculation of *Energy Take*. Right plot: Incorrect calculation of *Energy Take*. *Energy Take* data are in blue, power data are in red. In both cases, the ERWHs had been placed in *Shed* mode prior to receiving a *Load Up* request, at which point the heating elements turn on.

Table 1. Data related to the two plots within Figure 2 as well as to the discussions within Subsections 2.1 & 2.2

	ET Start (kWh)	Est. T_{tank} (°F)	Duration (m)	Power (kW)	Energy (kWh)	ΔE (kWh)
Left plot	2.2	112	29	4.1	2.0	-0.2 (9%)
Right plot	4.8	90	45	4.4	3.3	-1.5 (45%)

In the right-hand plot of Figure 2, the *Energy Take* at the start of the *Load Up* period (14:32) is the amount of electrical energy expected to be consumed during the *Load Up* period. Yet, the plot of power between 14:32 and 14:53 shows that ERWH is drawing power while *Energy Take* remains the same. During this period, the upper element was on. At 14:53, the upper heating element turns off and the lower element turns on. From this point forward, the *Energy Take* begins to decrease. In this case, the estimate of *Energy Take* was 45% too large. It appears that for the calculation of *Energy Take*, A = 1 and B = 0, essentially basing the calculation only on the higher temperature water in the upper portion of the tank while neglecting the cooler temperature water in the lower portion of the tank.

2.2 Excessively Deep Shed

Referring again to Figure 2 and Table 1, prior to initiating the *Load Up*, both units were placed in *Shed* mode. During this *Shed* period, the unit on the left turned on when the *Energy Take* had reached 2.2 kWh, which represents around 112°F, while the unit on the right did not turn on until there was 4.8 kWh of *Energy Take*, which represents around 90°F. In other words, the unit on the right allowed the unit to go all the way to 90°F during a *Shed* before turning on to prevent a cold-water event. This is clearly too low, and the customer is likely to experience a cold water event. This illustrates a conflict in expectations between the LME and the customer that the OEM must navigate when deciding how its products should respond to a *Shed* request. Anticipating that SGDs will receive frequent *Shed* requests, the decrease in T_{tank} during a *Shed* event should not lead to customer discomfort. On the other hand, the LME would like to dump as much energy as possible into available loads during a *Load Up* request, which would necessitate as deep a *Shed* as possible.

2.3 Erroneous Electric Power Reporting

The CTA-2045 *CommodityRead* request returns *Commodity Code* 0, which reports electric power consumption at the moment of query. This can be used to track electric power consumed by an SGD over time. However, the reported electric power is often a stored value rather than one calculated using measurements from meters within the unit. For ERWHs, this approach is reasonable since electric power consumption is usually rather close to 4.5 kW on a 240 V service, and using a stored value saves the OEM the expense of installing a current transducer within the unit. For HPWHs, using a current transducer and an assumption of voltage may be sufficient so long as the compressor motor power factor is near unity. OEMs can provide electric power estimates of HPWHs by using values that they may already be measuring—such as ambient, upper and lower tank temperatures, along with a CoP lookup table—to calculate where the compressor is on its power curve, without needing to install current transducers within their units.

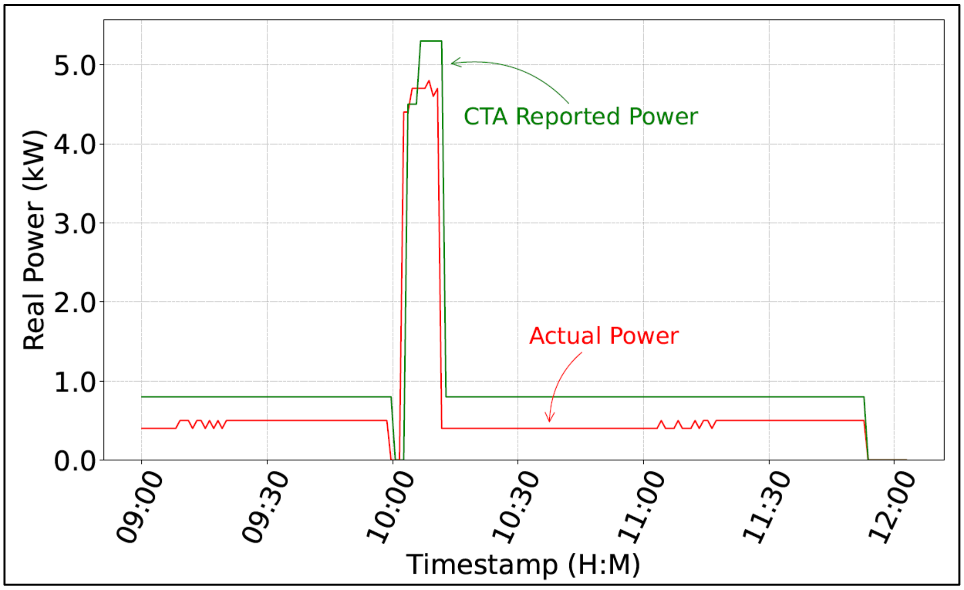

Figure 3. Reported and actual power consumption of an HPWH
Plots of power drawn by a 50 gallon heat pump water heater as reported via a *CommodityRead* request (green) vs. as measured via an external current transducer (red). During most of the reporting period, the heat pump compressor is on. The unit is subjected to a 20-gallon water draw at 10:00, prompting the heating element to turn on and draw an additional 4.5 kW.

Figure 3 shows power drawn by a heat pump water heater (HPWH). HPWHs have a heating element, which typically draws around 4.5 kW, and a compressor, which draws around 200 to 800 W, depending on the temperature differential across the compressor.[3] Note the two power plots within Figure 3. The green plot shows power logged via the CTA-2045 *CommodityRead* request, which is only ever 4500 W, 800 W, or the sum of the two. These come from stored values within the unit controller. The red plot shows power calculated using data from an external current transducer and an assumption of 240 V service (so it is actually reporting apparent power, VA; active power, W, would be slightly less), which increases over time as the internal tank temperature rises. The ~300 W difference between the two is small but would matter to an LME when compounded across a large aggregation of SGDs.

2.4 Incomplete Load Up

Figure 4 illustrates a case of incomplete *Load Up*. A resistance WH has an *Energy Take* of ~1000 Wh at 10:56 when a *Load Up* request is made. The unit responds to the request but the *Energy Take* does not decrease to 0 Wh; the heating element turned off prior to driving the *Energy Take* to 0 Wh, thus failing to fully heat the tank. This is an incomplete use of the *Energy Take* that the unit could have provided.

[3] As the temperature differential between the water in the tank and the ambient air rises, the compressor must consume proportionally more electrical energy to transfer a given amount of thermal energy into the tank.

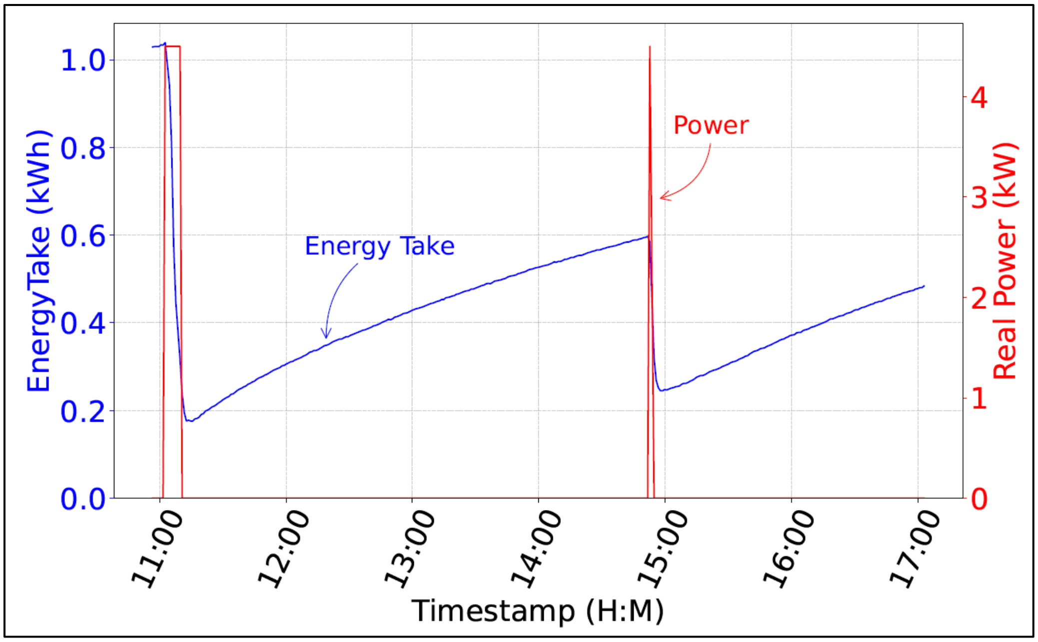

Figure 4. Observations of *Energy Take*
Following a *Load Up* request (11:00), *Energy Take* (blue) does not return to 0 Wh. During the *Load Up* period, a ~3°F dead band permits the *Energy Take* to increase to around 600 Wh (14:50) before the heating element comes on. Real power consumption (kW) is shown in red.

2.5 Load Up Dead Band

Consider Figure 4 again, which shows a resistance WH under a *Load Up* request starting at 10:56. During the *Load Up* period, an *Energy Take* dead band appears between 200 Wh and 600 Wh, corresponding to a dead band width of ~3°F, typical for a WH. A tighter dead band during the *Load Up* period would reserve a greater average *Energy Take*, which would benefit both the customer and the LME were the unit to subsequently enter a shed-type mode.

2.6 Differentiation Between Shed-Type Functions (Requests)

CTA-2045 offers three shed-type modes:

- A mild shed, called *Shed*, which an LME would call frequently, and which should not cause discomfort to the customer;
- A deep shed, called *Critical Peak Event*, to be called rarely while preserving minimal customer service; and
- A full shed, called *Grid Emergency*, to be called only during grid emergency situations and limiting service to prevention of equipment damage, such as frozen plumbing.

Figure 5 shows an ERWH being maintained in each of these three modes, and in *Normal* mode. Each of the three plots spans 48 hours. In the *Normal* (blue), *Shed* (green) and *Critical Peak Event* (purple) plots, the WH maintains a set point temperature by occasionally turning on the resistive element (red). Table 2 shows the upper and lower bounds of the *Energy Take* when the unit is in the *Shed* and *Critical Peak Event* modes. Threshold data for the *Grid Emergency* mode (orange) were not determined because the tank temperature never dropped below the *Grid Emergency* set point.

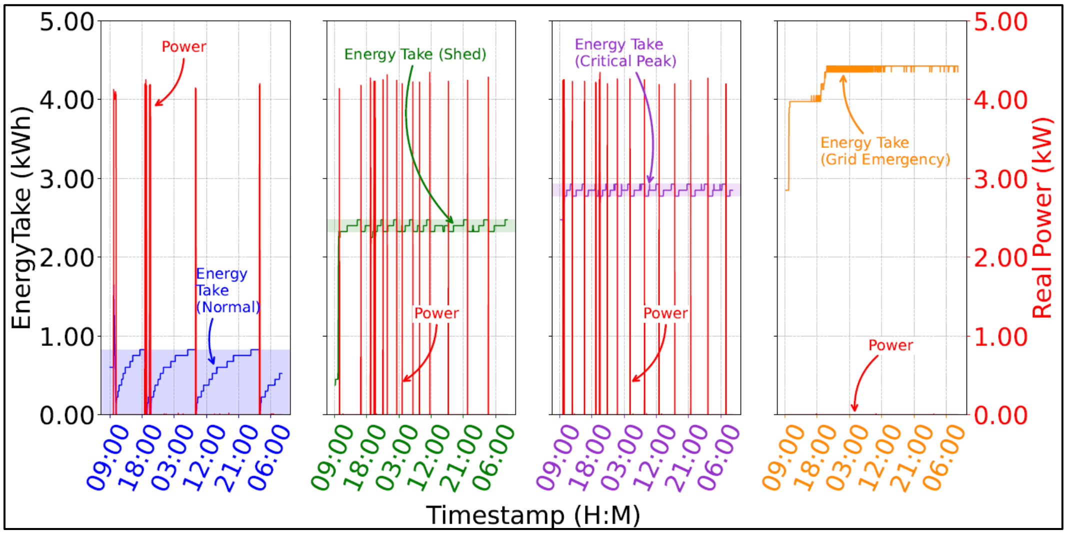

Figure 5. *Energy Take* in *Normal* mode and for three shed-type modes. A resistance WH in *Normal* mode and three different shed-type modes: *Shed*, *Critical Peak Event*, and *Grid Emergency*, maintained over a 48 hour period. Periodic spikes in power maintain the tank temperature within a dead band around the mode set points.

Note the difference of only 450 Wh between the *Energy Take* in the *Shed* and *Critical Peak Event* modes, corresponding to set points around 110°F and 105°F for the two modes, respectively (note too that the data have a rather wide ±75 Wh resolution, and that ~1°F represents ~110 Wh for a nominal 50-gallon WH). In addition, the *Shed* mode set point is quite far from the baseline set point of 130°F, meaning a significant chance that this low set point could result in customer discomfort.

Table 2. Upper and lower bounds of the *Energy Take* dead bands for a resistance water heater in *Shed* mode and in *Critical Peak Event* mode, and approximate tank temperatures

	Upper	Lower
***Shed* (Wh)**	2,475	2,325
Est. T_{tank}(°F)	110	111
CPE (Wh)	2,925	2,775
Est. T_{tank}(°F)	106	107

2.7 Differentiation in Total Energy Storage Capacity

Customer water temperature preferences will change the *Total Energy Storage* capacity, which is read by issuing a *CommodityRead OpCode 6.* This value is a constant determined by the minimum tank temperature, as defined by the OEM, and the customer temperature set point. For example, a customer with a 130°F set point will have a high *Total Energy Storage* capacity due to the range of temperatures available to that customer, compared to a customer with a 110°F set point.[4]

Table 3 shows *Energy Take* capacities for two water heaters from different manufacturers. Advertised *Op Code 6* may differ by more than 100% when looking at water heaters from different OEMs of the same tank volume. The implications of the available *Energy Take* capacity may affect calculations for energy consumed if the customer lowers the tank temperature below *Op Code 6* capacity.

Table 3. Upper and lower bounds of *Energy Take* and approximate tank temperatures of two different resistive WHs in *Shed*

	T_{set} (°F)	Op Code 6 (kWh)	T_{min} (°F)	T_{upper} (°F)	T_{lower} (°F)	ΔT_{upper}	ΔT_{lower}
WH A	130	9.8	39	106	97	18%	25%
WH A	110	7.4	42	107	98	3%	11%
WH B	130	4.4	91	109	108	16%	17%
WH B	110	2.9	84	99	97	10%	12%

2.8 Internal Temperature Set Point in Shed

When a WH responds to a *Shed* request, the internal set point is shifted lower to some degree, as determined by the OEM, in order to defer energy consumption during the service period. Table 3 shows how two different WHs respond to a *Shed* request, at differing customer set points.

During a *Shed* service, WH A lowered the internal set point to nearly the same values, 106°F/97°F vs. 107°F/98°F, whether the customer set point was 110°F or 130°F, respectively. WH B lowered the internal set point to different values relative to customer set point, 109°F/108°F when T_{set} = 130°F vs. 99°F/97°F when T_{set} = 110°F. The former may cause discomfort to customers with higher temperature expectations, lowering the internal set point by 24°F, relative to customers whose 110°F set point is lowered by a modest 3°F. This may cause issues for both customers and utilities. A temperature of 106°F will be more noticeable to a customer expecting 130°F than to a customer expecting 110°F. When a utility is requesting grid services, it may see an 18% shift for one WH and a 3% shift for another, making planning in aggregate more difficult.

2.9 Energy Take Non-return to Zero

Figure 6 illustrates a case in which *Energy Take* fails to return to 0 Wh. In *Normal* mode, the *Energy Take* (*Commodity Code* 7, blue) should return to 0 Wh and the customer should expect water temperature to return to the customer-defined temperature set point. However, this unit does not return *Energy Take* to 0 Wh during any of the performed tests; in this case, customer expectations are not being met. The ~300 Wh minimum *Energy Take* represents a deviation from the set point temperature of ~2.5°F.

[4] 110°F is a rather low customer set point, used in this document to represent a corner case.

A test was performed to measure the temperature of the water after a *Load Up* command request was sent. Water was drawn immediately after the WH heated to the lower *Energy Take* threshold in *Load Up*. The measured temperature of the water was indeed lower than the customer set point, deviating by ~ 5°F. Temperature stratification in the tank can cause deviations from measured tank temperature, which is used to calculate *Energy Take*. Since the temperature deviation from *Load Up* tests deviated beyond what was expected from the lower *Energy Take* set point, the result of this issue may be a combination of both an inaccurate *Energy Take* and an incomplete *Load Up*.

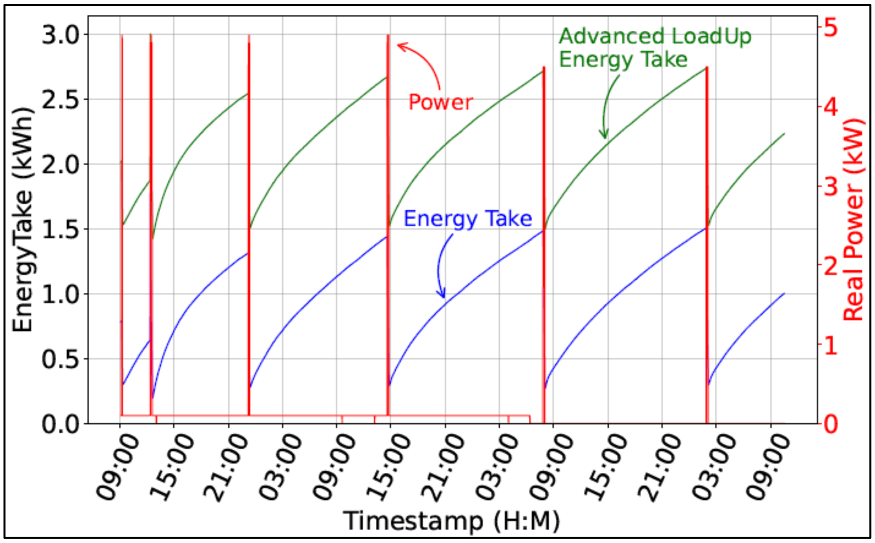

Figure 6. Observations of *Energy Take and Advanced Load Up Energy Take* Baseline testing of an electric resistance WH reporting *Commodity Code* 7, *Energy Take* (blue), and *Commodity Code* 11, *Advanced Load Up Energy Take* (green), which is offset from *Energy Take* by 1230 Wh.

2.10 Energy Take Data Resolution

CommodityRead data reported by the units highlighted in this study show *Energy Take* data resolution ranging from 4 Wh to 75 Wh. Obi et al. observed a CTA-2045- enabled WH with a data resolution of 1,500 Wh (Obi 2021). A 1°F temperature variation corresponds to ~110 Wh in a nominal 50-gallon water heater. Large *Energy Take* resolutions correspond to uncertainties in time and temperature. For instance, a 4,500 W heating element would take about 1.5 minutes to transfer that much energy into the tank. And typical set point dead bands are ±2.5°F –3°F.

2.11 Conflicting CommodityRead Data

This last example is actually a compliance error rather than a conformance problem. Figure 6 also shows *Energy Take* and real power data from a test of WH behavior under baseline conditions. The unit was subjected to a 24-hr water draw profile followed by a 24-hr idle period.

Two *Energy Take* values were reported during the test period, with one uniformly offset from the other by 1,230 Wh. Both values were erroneously reported as *Commodity Code* 7. As such, this issue is a compliance error. A sample of reported data is shown in Figure 7.

```
Sun Dec  3 10:16:11 2023, 0, 208976, 0, 6, 9833, 0, 7, 990, 0, 10, 11062, 0, 7, 2219, 0, 0, 0
Sun Dec  3 10:17:11 2023, 0, 208976, 0, 6, 9833, 0, 7, 990, 0, 10, 11062, 0, 7, 2219, 0, 0, 0
Sun Dec  3 10:18:12 2023, 0, 208976, 0, 6, 9833, 0, 7, 992, 0, 10, 11062, 0, 7, 2221, 0, 0, 0
Sun Dec  3 10:19:12 2023, 0, 208976, 0, 6, 9833, 0, 7, 992, 0, 10, 11062, 0, 7, 2222, 0, 0, 0
Sun Dec  3 10:20:13 2023, 0, 208976, 0, 6, 9833, 0, 7, 993, 0, 10, 11062, 0, 7, 2222, 0, 0, 0
Sun Dec  3 10:21:14 2023, 0, 208976, 0, 6, 9833, 0, 7, 995, 0, 10, 11062, 0, 7, 2224, 0, 0, 0
Sun Dec  3 10:22:14 2023, 0, 208976, 0, 6, 9833, 0, 7, 996, 0, 10, 11062, 0, 7, 2225, 0, 0, 0
Sun Dec  3 10:23:15 2023, 0, 208976, 0, 6, 9833, 0, 7, 996, 0, 10, 11062, 0, 7, 2225, 0, 0, 0
```

Figure 7. Time series data returned by a *CommodityRead* request
Highlighted in red boxes, *Commodity Code* 7—present *Energy Take*—is reported twice, with different values offset by 1,230 Wh. The higher values should have been reported as *Commodity Code* 11, present *Advanced Load Up Energy Take.* These data are plotted in Figure 6.

Nonetheless, the error passed compliance testing. Two different test tools were being used when this error was discovered, one by the OEM and the other by the Portland State University power engineering laboratory. The OEM's tool was reporting the first instance of *ComCode* 7 while PSU's was reporting both. A third tool, the Electric Power Research Institute's (EPRI's) CTA-2045 client, was then connected and found to be reporting the latter *ComCode* 7.[5]

The lower *Energy Take* (blue) was being properly reported as *ComCode* 7. The higher *Energy Take* (green) was also being reported as *ComCode* 7 when it should have been reported as *ComCode* 11, *Advanced Load Up Energy Take.* This example emphasizes the importance of consistency in reporting *ComCode* data so that LMEs receive reliable information from flexible load resources.

[5] None of these three testing tools is the compliance test tool used by Underwriters Laboratories and made by SkyCentrics.

3 Basic Responses to CTA-2045 Messaging

Following are brief descriptions of expected behaviors for WH responses to *Load Up* and *Shed*-type requests. Also included for each event type are the California Title 24 Building Energy Efficiency description from Joint Appendix 13, and wording from AHRI 1430-2022, the standard for Demand Flexible Electric Storage Water Heaters (CEC 2022; AHRI 2023).

3.1 Expected Behaviors: Shed-Type Events

3.1.1 Shed: A Light Shed Event

While in *Shed* mode, the SGD should use less energy, coming on briefly to prevent cold water events when necessary. Per CA Title 24 JA13: *"The System will defer complete recovery for the duration of the shed event unless user needs cannot be met; The water heater shall avoid use of electric resistance elements during and immediately after the event unless user needs cannot be met."* AHRI 1430-2022 makes a similar statement: *"General Curtailment [Shed] directs the water heater to prevent using energy that the device otherwise uses under normal mode of operation. …the DFWH [demand flexible water heater] shall use the most efficient heating mode, during and immediately after the event unless user needs cannot be met."*

AHRI 1430-2022 states that WHs with nominal storage capacities less than 50 gallons shall be able to load shift 0.25 kWh, and WHs with nominal capacities between 50 and 120 gallons shall be able to load shift 0.50 kWh (AHRI 2023). For a nominal 50-gallon WH, 0.50 kWh corresponds to a setback of less than 5°F.

3.1.2 Critical Peak Event: A Deep Shed Event

While in *Critical Peak Event* mode, the SGD should use minimal energy, more aggressively than *Shed*, and come online only briefly to prevent short duration cold water events. Per CA Title 24 JA13: *"Same as Light Shed, but the System will completely avoid use of electric resistance elements during the event."* AHRI 1430- 2022 states that a Critical Curtailment shall use *"…stored thermal energy in the tank to supplement up to a lower depleted level than for General Curtailment."*

3.1.3 Grid Emergency: A Full Shed Event

While in *Grid Emergency* mode, the SGD should use a minimal amount of energy, if any, short of causing safety or equipment damage issues. Per CA Title 24 JA13: *"Same as Light Shed, but the System will completely avoid use of both compressor and electric resistance element during the event."* AHRI 1430-2022 permits use of heating methods when the unit is in a *Grid Emergency* mode, considering safety: *"Grid emergency directs the DFWH to immediately stop using energy for water heating when it is safe to do so."*

3.2 Expected Behaviors: Load Up-Type Events

3.2.1 Basic Load Up

During a *Load Up* event, the SGD should turn on immediately, unless it is very close to the temperature set point. The SGD should have a reduced dead band as long as the *Load Up* event is in effect, to keep water temperature as close to the set point as possible. Per CA Title 24 JA13: *"For a water heater sized in accordance with JA 13.3.2(b) and with the default set point as shipped from the manufacturer, the System shall be able to shift: A minimum of 0.5 kWh of user electrical energy per (Basic Load Up + Light Shed) event."* AHRI 1430-2022 states that *"Basic Load Up directs the DFWH to use or store or both, additional thermal energy that the device does not use or store under normal mode of operation… within the parameters set by the manufacturer up to the user set point."*

3.2.2 Advanced Load Up

This higher performance *Load Up* can generally be achieved by increasing the tank temperature set point. After receiving an *Advanced Load Up* request, the WH should turn on immediately, unless the tank temperature is very close to the set point. Once the set point is reached, the WH should come on frequently to maintain a high level of stored energy. This could be done using a dead band that is narrower than the usual dead band.

Delivery performance based on CA Title 24 JA13: *"For a water heater sized in accordance with JA 13.3.2(b) and with the default set point as shipped from the manufacturer, the System shall be able to shift: A minimum of 1 kWh of user electrical energy per (Advanced Load Up + Light Shed) event, including at least 0.5 kWh on Advanced Load Up."* AHRI 1430-2022 states that *"Advanced Load Up allows the stored thermal energy to increase within the parameters set by the manufacturer beyond user set point."*

4 Recommendations

4.1 Unique Shed Behaviors

Generally, routine grid service response participation should maximize availability of the SGD for the grid service program while minimizing discomfort for the customer. To provide this flexibility, there should be unique shedding behaviors between shed-type functions (see Subsection 2.6). *Shed* should perform differently than *Critical Peak Event* and *Grid Emergency.* According to CTA-2045, *Shed* shall be used most frequently, followed by *Critical Peak Event* and *Grid Emergency,* both of which are to be used rarely.

Since *Shed* is expected to be used frequently, OEMs should consider behaviors that would have little chance of impacting customer comfort. Excessively deep *Shed* events should not occur (see Subsection 2.2). A *Critical Peak Event* should result in a large deviation from the customer's temperature set point to support minimal appliance use, while a *Grid Emergency* should prioritize preventing damage to the unit (e.g., pipe freezing).

LMEs need to mind the intention of the *Grid Emergency* mode; it is to be used sparingly, in cases of grid emergency such as during recovery from loss of service or load reduction for wildfire mitigation. *Grid Emergency* shall not be used as a means for implementing direct load control (DLC), wherein the SGD is shut off for a duration subject to the whim of the LME.

With regard to heat pump WH units, the WH controller should prioritize the use of non-resistive heating during *Shed* mode unless customer needs cannot be met. While in *Critical Peak Event* and *Grid Emergency* modes, the controller should be programmed to use only the compressor (minimal power), if water must be heated at all.

4.2 Present Energy Take

Reported *Energy Take* capacities, for both *Commodity Codes* 7 and 11, should be close to the amount of energy the SGD would consume after receiving a *Load Up* or *Advanced Load Up* request, respectively (see Subsection 2.1). These capacity estimates will be related to how tank temperature is calculated using a limited number of temperature sensors, as well as several other factors, as discussed in Subsection 1.4. Whether using weighted values on upper and lower tank temperatures or another method, implementation of the algorithm should be validated.

4.3 Reported Power Consumption

Reported real power consumption, *Commodity Code* 0, should be reasonably close to actual power consumption (see Subsection 2.3). Using stored register values is sufficient for resistance water heaters, and probably sufficient for estimating the power consumption of heat pump water heater compressors, which do not experience large ΔT ranges. However, the estimates must be reasonable, counter to the data shown in Figure 3.

4.4 Data Resolution

The resolution of reported *Commodity* data should be constrained by the resolution of sensors and the uncertainty of assumed values, rather than, say, a set sampling rate or a register size. In the case of *Energy Take*, data resolution should be small enough such that actuation of CTA-2045 methods is not delayed by minutes, nor should temperature uncertainties be a significant fraction of a typical dead band. During rapid heating and large water draw events, thermal lag due to convective heat transfer of water within the tank will result in reporting *Energy Take* data that does not represent the actual *Energy Take* of the tank. However, high resolution transient data can show a trend toward the actual, steady-state *Energy Take*. In future, one could imagine sophisticated UCMs fitting exponential decay models to sampled data to infer steady-state *Energy Take*, for example.

4.5 Implementation of Load Up

Load Up and *Advanced Load Up* should trigger an SGD to respond immediately and drive its *Energy Take* to 0 Wh, unless the control variable is within the dead band around the set point (see Subsection 2.4). A *Load Up* request should also modify the dead band around the set point. By narrowing the dead band, the unit is more likely to turn on during a *Load Up* event and is more likely to maintain stored thermal energy in preparation for a subsequent shed-type event, contrary to the behavior shown in Figure 4. For example, if the dead band is ±6°F around 130°F, the *Load Up* dead band should less than that, perhaps ±3°F. However, these decisions should be left to the OEMs, who are best able to determine safe operation of their equipment. For instance, frequent cycling of heating element relays can shorten product lifetime.

Some OEMs impose limits on relay cycling, for instance a maximum of 24 cycles per 24 hours and an average of 12 cycles per day within a 100-day period. In such cases, narrower *Load Up* dead bands would deplete the relay cycle budget. Along these lines, LMEs should limit the use of *Load Up* to time periods just prior to *Shed* events and keep *Load Up* durations short, rather than holding units in *Load Up* modes for long periods.

4.6 Reporting Advanced Load Up Energy Take

SGDs capable of responding to an *Advanced Load Up* request should report both *Energy Take*, *Commodity Code* 7, and *Advanced Load Up Energy Take*, *Commodity Code* 11, when sent a *CommodityRead* request. Reporting of *ComCode* 11 should occur regardless of the unit's mode at the time. For example, *ComCode* 11 should not change when the unit transitions from *Normal* mode to *Advanced Load Up* mode. The WH should report both *Energy Take* and *Advanced Load Up Energy Take* at all times, even when the unit is not in *Advanced Load Up* mode, as shown by the blue and green curves, respectively, in Figure 6. By reporting both *Energy Take* values at all times, the LME will understand the full load up potential of the unit.

4.7 Mode-Varying Dead Bands

SGDs that use dead bands around set points should use different dead bands depending on the mode the unit is in. Dead bands are used to minimize unit cycling. By providing some buffer around a set point, deviations in the control variable will not trigger frequent and brief power draws. In *Normal* mode, *Critical Peak Event* and *Grid Emergency* modes, standard dead bands should be used to minimize unit cycling. OEMs should consider applying more narrow dead bands when units are in a couple of other CTA-2045 modes, described below.

4.7.1 Shed Dead Band

When in *Shed* mode, SGDs should have a narrower dead band. If the set point has been lowered, more frequent cycling would minimize instances of customer discomfort, and the LME would be able to better estimate the expected contribution of energy storage capacity.

4.7.2 Load Up & Advanced Load Up Dead Bands

When in load up modes, SGDs should have a narrower dead band. Doing so would maximize energy consumption during the load up period, increase the amount of stored thermal energy in preparation for a subsequent shed-type event, and increase the likelihood that the unit would respond to a *Load Up* request immediately upon receiving the request.

4.8 Advanced Load Up

4.8.1 CTA-2045 Change Recommendations

CTA-2045 provides a means for specifying the energy efficiency of the HPWH response to an *Advanced Load Up* request, called the “SGD Efficiency Level” OpCode.[6] Currently, implementation of this OpCode is optional. OEMs should define responses to the nine levels of this OpCode. OEMs would need to define specific responses to each of these levels, from low efficiency (e.g., resistive element only) to highest efficiency (e.g., HP only).

Specifying these responses would increase the value of the products to both LMEs and customers. A low OpCode *Advanced Load Up* request from LMEs would allow the customers’ units to engage only the heat pump, thereby minimizing customer utility bills. Alternatively, units would respond to a high OpCode *Advanced Load Up* request by using the resistive heating element, thereby allowing the LME to rapidly dispatch SGDs in response to a grid event. Or, the LME could send a moderate OpCode *Advanced Load Up* request that would enable units to turn on in the manner best-suited to recovering thermal energy, thereby avoiding cold water events.

4.8.2 Pre-install Mixing Valves

A mixing valve should be in place so customers experience consistent hot water temperature and the chances of scalding are minimized, as required by AHRI 1430-2022, Appendix E.

OEMs should manufacture WHs with mixing valves pre-installed in the product. Requiring the customer to hire a plumber to install the mixing valve will increase installation cost and decreases manufacturer trust that the system is well-installed. Mixing valves should be easy for the customer or plumber to replace in case the valve fails.

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[6] ANSI/CTA-2045-B Section 11.6

4.9 Other OEM Responsibilities

4.9.1 EcoPort™ Readiness

Ensure the CTA-2045 EcoPort™ is fully functional before it leaves the factory. A separate EcoPort™ add-on should not be required. It must have power and communication lines connected and be "ready to go." The customer should not have to rely on following installation instructions. The customer should be able to simply plug the UCM into the EcoPort™ and not have to interact with OEM software to enable the UCM to start communicating. Installation of the CTA-2045 EcoPort™ should infer that the customer intends to enroll into LME DR programs. Upon installation of the UCM, the SGD should be enabled for grid interactivity with grid services.

4.9.2 Communication Independence

Ensure the EcoPort™ is fully independent of any other OEM communications. In other words, whether the OEM Wi-Fi exists or whether the unit is connected to the OEM cloud should not impact the functionality of the EcoPort™ communication; it should always work if a UCM is connected. It should also override any schedule that the OEM scheduler has in place, with the exception of Vacation Mode (SGD Efficiency level 10), in which case the override should last for as long as the customer keeps the unit in that mode.

4.9.3 Grid Mode Override

The only condition that should prevent an event from occurring is when the customer has entered an override command request. The override should not exceed 72 hours (with the exception of Vacation mode). The customer should not have to do anything to "end the override," otherwise, the availability of the SGD to the LME may be negatively impacted.

4.10 Rapid Responses to CTA-2045 Requests

Issues with fast-response SGDs could negatively impact the deployment of grid services, particularly with requests for *Load Up*, *Advanced Load Up* and *EndShed*. Compressor-based loads draw significant in-rush current upon startup, and thermostatically controlled loads will turn on immediately upon being re-energized if their control variable is below the unit set point, known as "cold-load pickup."

In large aggregations, actuation of SGDs could trip power system overcurrent, under-/over-voltage, or, in rare cases, under-/over-frequency protection devices. This is often referred to as "snap-back," and is often seen in Time-of-Use DR programs and peak-time rebate DR programs. In response to load up requests, such loads have the potential to draw significant current at the start of an event. Beginning or ending grid services that use fast-acting SGDs can, in sufficient numbers, impact local voltages as well as system frequency in small island systems.

These issues can be addressed either by LMEs or OEMs. LMEs can stagger the dispatch of SGDs over a managed "ramp-up" period; OEMs can build soft start or randomized delay procedures into their products. Other smart grid standards include such randomized start options (IEEE 2030.5, SunSpec Modbus) (IEEE 2018; SunSpec 2015). Such features could be considered for future versions of CTA-2045. For example, when power returns to an SGD, the SGD could provide a "heartbeat" to the UCM, which would then delay restart (perhaps via *Shed*) of the SGD by a prescribed period of time. If such a system were implemented within the CTA-2045 standard, the range of the randomization period would need to be considered in the context of fairness for the consumers.

5 Moving Forward

All water heaters featured in this document exhibited good conformance behaviors in response to CTA-2045 requests, though not for all requests. Every SGD that Portland State University has tested to date could benefit from improved request responses. Conformance improvements might come about if OEMs had a better understanding of how their products play a role in delivering utility grid services. However, grid services are not within the OEMs' domain of expertise, nor should they be expected to develop this expertise. The delineation of expertise within the flexible load management stack should be respected.

Rather, SGD OEMs would benefit from partnering with a third party, such as the Northwest Energy Efficiency Alliance, that provides conformance guidance. Such guidance could be done by publishing conformance guidance documents for specific categories of SGDs and by offering workshops or seminars to OEMs. These services would help OEMs understand how their products could best respond to CTA-2045 messaging while concurrently providing high quality service to their own customers.

These guidance products would be designed to provide OEMs with a big-picture perspective of the full flexible load stack, though with discussion emphasis on how SGDs could best respond to CTA-2045 messaging. Seminar presenters would bring expertise from the grid operating and LME perspectives and abstract the needs of those layers in a way that translates to effective SGD responses to CTA-2045 messaging. Participants would gain an understanding of the value that their products could bring to LMEs (and indirectly to their own customers) while participating in an in-depth discussion of CTA-2045 conformance. Seminar presenters would also have an opportunity to learn about the OEMs' design concerns and their visions for SGD evolution.

Customers benefit when their SGDs are dual optimized to provide high-quality appliance performance and to contribute constructively to grid service programs. Their electric utilities will be able to provide them with more reliable and carbon-free electricity, they will have opportunities to use their appliances as revenue-making SGDs, and their appliances will reliably deliver quality and comfort.

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