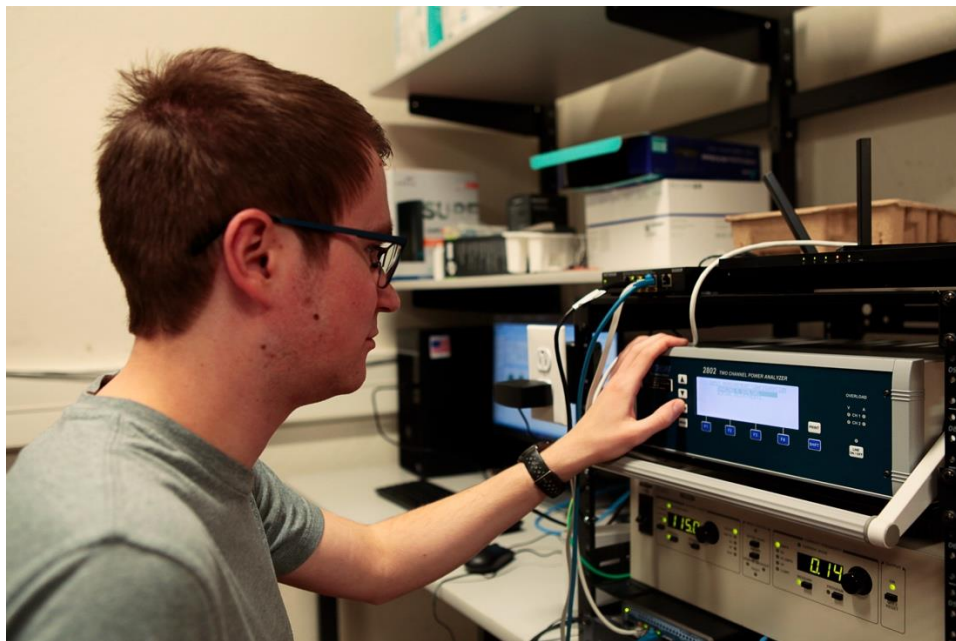


Performance Evaluation of Advanced HEMS

Final Report

ET22SWE0055



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Executive Summary

The Performance Evaluation of Advanced Home Energy Management Systems (AHEMS) project conducted a laboratory assessment of multiple residential energy platforms to measure efficiency, operational behavior, and their potential contributions to grid flexibility. The systems tested reflect a range of market maturity, from commercially deployed solar-plus-storage platforms to early-stage DC-bus and V2X architectures. Across all tested transmission pathways, two systems, AHEMS 2 and AHEMS 4, demonstrated high electrical efficiency, with measured values ranging from approximately 90–94 percent for AHEMS 2 and 94–99 percent for AHEMS 4. Battery-related pathways, such as grid charging and discharge to loads or the grid, exhibited the most consistent performance, while solar export pathways showed greater variability due to inverter control behavior and regulation dynamics.

Despite similar hardware performance, the systems showed significant divergence in control strategy during Time-of-Use operation. AHEMS 2 followed a predictable tariff-aligned dispatch pattern, discharging during peak periods and recharging overnight, reflecting deliberate design for cost optimization. In contrast, AHEMS 4, though highly efficient at the hardware level, displayed irregular dispatch behavior, including off-peak discharging and missed charging opportunities, resulting in economically counterproductive outcomes. These findings indicate that software-controlled logic, rather than raw electrical efficiency, is now the primary determinant of real-world system value.

An economic analysis of AHEMS 2 under PG&E's E-ELEC rate structure estimated a potential net annual benefit of approximately \$1,492 using retail-rate assumptions, driven by strategic export during high-value pricing windows. While actual compensation under NEM 3.0 would likely reduce this figure due to lower avoided-cost export crediting, the analysis confirms that AHEMS platforms with coherent TOU logic can deliver meaningful bill savings when properly configured. In parallel, greenhouse gas impacts were evaluated using California's Low Carbon Fuel Standard grid emissions factor of 290 gCO₂e/kWh. Under sustained TOU operation, AHEMS 2's behavior yielded an estimated 4,464 kgCO₂e of avoided emissions annually by reducing reliance on grid imports during carbon-intensive periods.

Two systems featuring DC-bus architectures and V2H capabilities, AHEMS 1 and AHEMS 3, were acquired but could not complete testing due to various prototype limitations, including hardware instability and incomplete software integration. Their current readiness suggests that while V2X-capable platforms are a promising direction, they require further development before they can be evaluated. Taken together, the results reveal a key market insight: while AHEMS hardware efficiency is consistently high across various transmission pathways, the differentiation in customer benefits lies in the implementation and testing of control logic and the ability to align system behavior with economic, resiliency, and emissions objectives.

Abbreviations and Acronyms

Acronym	Meaning
AC	Alternating current
AHEMS	Advanced home energy management systems
BESS	Battery energy storage systems
CLTC	California Lighting Technology Center
CV	Coefficients of variation
DUT	Device under test
DC	Direct current
DERs	Distributed energy resources
EV	Electric vehicle
EVSE	Electric vehicle supply equipment
gCO ₂ e/MJ	Gallons carbon dioxide equivalent per megajoule
GHG	Greenhouse gas
HVAC	Heating, ventilation, and air conditioning
HEMS	Home energy management systems
IOU	Investor-owned utilities
kgCO ₂ e	Kilograms of carbon dioxide equivalent
kWh	Kilowatt-hour
PV	Photovoltaics
RASS	Residential Appliance Saturation Survey
REA	Residential energy and automation
TOU	Time-of-Use
V2H	Vehicle-to-Home
V2G	Vehicle-to-Grid

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Introduction

Advanced home energy management systems (AHEMS) represent an expanding category of technologies designed to optimize and improve residential energy use. These systems offer a range of innovative functions, including home energy management via panel-level controls, seamless integration with home appliances through appliance-specific communication channels, and grid-level demand response features—such as price-based or GHG-based load shifting or shedding—aimed at saving the customer money or reducing their overall carbon footprint.

The most capable AHEMS can provide consolidated management of distributed energy resources (DERs), including solar photovoltaics (PV), battery energy storage systems (BESS), and electric vehicle supply equipment (EVSE). By integrating these systems, AHEMS aim to enhance and optimize overall transmission efficiencies between resources; improve load flexibility of the home by dynamically modifying transmission pathways, such as rerouting flow between solar, storage, EVs, and household loads based on real-time conditions; and intelligently respond to external conditions such as grid outages, ensuring the continuous operation of essential home functions.

These subset of AHEMS are categorically referred to as residential energy and automation (REA) systems; a prior market study conducted by the California Lighting Technology Center (CLTC) found that these systems could potentially unlock 44 gigawatt-hours of energy yearly and have a potential peak hour (5:00 to 6:00 p.m.) reduction of 18.51 megawatts from grid flexibility via load shifting if just 5 percent of investor-owned utilities (IOU) customers with existing DERs installed a REA.

This project, the Performance Evaluation of Advanced HEMS, involves a comprehensive laboratory assessment of a subset of AHEMS that offer the most robust set of system capabilities. Through laboratory testing, the project focuses on quantifying the electrical efficiency and integration capabilities of these select AHEMS to verify system manufacturer performance claims. The systems will be subjected to a variety of scenarios based on possible daily operations routines while managing simulated and real energy loads to provide a clearer picture of system behavior and overall energy efficiency from a holistic viewpoint.

Background

A home energy management system is a technology designed to monitor, control, and optimize energy consumption within a residential setting. HEMS typically integrate with various home devices and energy sources, enabling homeowners to manage their energy usage more efficiently, which leads to cost savings and reduced environmental impact.

Features generally found in HEMS include:

- Real-time tracking of energy consumption across different appliances and systems within the home.
- Remote or automated control of devices, such as heating, ventilation, and air conditioning (HVAC) systems; lighting; and appliances to optimize energy use.

- Management of energy generated from renewable sources like solar panels, including storage solutions.
- Ability to adjust energy usage in response to utility signals or pricing changes to reduce peak demand.

Often, a home may have numerous HEMS acting independently within an environment designed to solely optimize a singular process, such as lighting, HVAC, or electric vehicle (EV) charging. With HEMS capabilities growing, there was a need for a more holistic AHEMS that would be the main host for all energy management capabilities, in addition to unlocking further energy opportunities through simplifying energy transmission pathways. The newly emerged REA systems aimed to address these shortcomings.

This project directly builds on the findings of ET22SWE0049 Market Study of Emerging Residential Energy and Automation Technology. ET22SWE0049 explored the REA system market, focusing on their published capabilities, installation needs, and operating requirements. The report investigated market opportunities and identified a potential California customer base who would immediately benefit from a REA system (Lopez, et al. 2024).

Objectives

This project's primary objective is to conduct a thorough investigation of advanced home energy management systems through a laboratory evaluation of up to four systems, which represent a range of technologies and features. The selected systems underwent a comprehensive assessment focused on critical performance metrics, including efficiency, interoperability, and load flexibility. To achieve this, the project team developed a detailed test methodology that simulates real-world conditions, addressing electrical efficiency, communication protocols, system interoperability, and electric vehicle charging capabilities (including bi-directional functionality). A residential testbed was constructed to replicate typical home environments, incorporating standard electrical loads, programmable loads, DERs inputs, power analyzers, a solar array, an energy storage system, and an electric vehicle supply equipment.

The project aimed to execute laboratory testing in a controlled and repeatable manner, ensuring consistent conditions across all evaluated systems. The team analyzed collected data to quantify incremental performance improvements and assess system capabilities, based on metrics such as electrical efficiency, annual energy savings, peak load reduction, and load flexibility. The project will culminate in a Final Report that synthesizes findings and offers recommendations for system improvement. This report will be disseminated to stakeholders, including residential contractors, utility programs, developers, and manufacturers of residential control systems, supporting broader market adoption and utility program implementation.

Methodology and Approach

This evaluation combined prior market research with controlled laboratory testing to ensure both a broad understanding of available AHEMS and a rigorous assessment of system performance under real-world operating conditions. The methodology followed two major steps:

System Selection Methodology

In this project, the research team surveyed REA systems from a range of manufacturers to identify those with the most advanced capabilities. The goal was to prioritize systems that offered the greatest potential for energy efficiency, flexibility, and integration across residential energy resources.

Laboratory Evaluation Approach

Once the team identified and acquired systems, controlled laboratory testing was conducted to validate manufacturer performance claims. The testing approach is divided into two phases:

- **Efficiency Characterization**, measuring performance of applicable individual energy transmission states (e.g., solar to grid, battery to grid, vehicle to battery).
- **Scenario-Based Evaluation**, observing system responses to sequences of simulated daily operating conditions and events, with metering of system performance and behavior over time.

The detailed testing framework, configurations, and protocols are presented in the [Testing Methodology](#) section of this report.

System Selection

[Table 1](#) summarizes the REA systems reviewed in this project, highlighting their integration features, DERs management capabilities, and potential contributions to residential energy efficiency. The comparison illustrates the diversity of available approaches while providing a basis for identifying the most capable systems for further evaluation.

Table 1: Identified advanced HEMS and integration capabilities.

Advanced HEMS	DER Capabilities	Appliance/Load Control	Developmental Status
AHEMS 1	EV, PV, BESS	No	Prototype
AHEMS 2	Limited EV, PV, BESS	Yes, Dedicated Circuits	Prototype
AHEMS 3	EV, PV, BESS	Yes, through networked load controllers	On Market/ Prerelease
AHEMS 4	EV, PV, BESS	Yes, through networked load controllers	On Market

Advanced HEMS	DER Capabilities	Appliance/Load Control	Developmental Status
AHEMS 5	EV, PV, BESS	No	On Market
AHEMS 6	EV, PV, BESS	Yes, through networked load controllers	On Market
AHEMS 7	EV, BESS	Yes, Through Smart Panel	On Market
AHEMS 8	EV, PV, BESS	Yes, Through Smart Panel	Prototype
AHEMS 9	PV, BESS	Yes, Through Smart Panel	Prototype
AHEMS 10	BESS	Yes, Through Smart Panel	On Market

Source: CLTC.

The research team conducted an extensive literature review of existing documentation and engaged directly with manufacturers and system representatives to obtain detailed insights into unspecified system characteristics and anticipated future product developments. [Table 2](#) presents the identified system capabilities through manufacturer specifications, highlighting features that have the potential to impact overall efficiency and optimization within residential energy management.

The transmission efficiency sections indicate the efficiency from both solar panel outputs and BESS to the home, while the EVSE connector sections specify the supported EVSE charger for each advanced HEMS. Lastly, the EVSE bidirectional capabilities section reports on Vehicle-to-Home (V2H) and Vehicle-to-Grid (V2G) functionality.

Table 2: Identified advanced HEMS and transmission efficiencies.

Advanced HEMS	Solar Transmission Efficiency	BESS Transmission Efficiency	EVSE Connector	EVSE Bidirectionality Capabilities
AHEMS 1	96	97.5	CCS1	V2H; V2G
AHEMS 2	96	96	Any plug based 240V EVSE	Not Supported
AHEMS 3	98.4	97.5	CHAdEMO/CCS1	V2H; V2G
AHEMS 4	99	94.5	SAE J1772	Not Supported
AHEMS 5	97.5	90	NACS/J1772	Not Supported
AHEMS 6	97	89	SAE J1772	Not Supported
AHEMS 7	N/A	97.5	SAE J1772	Not Supported

Advanced HEMS	Solar Transmission Efficiency	BESS Transmission Efficiency	EVSE Connector	EVSE Bidirectionality Capabilities
AHEMS 8	98	Unknown	SAE J1772	Not Supported
AHEMS 9	Unknown	Unknown	N/A	N/A
AHEMS 10	N/A	97.5	N/A	N/A

Source: CLTC.

The system selection process prioritized AHEMS with advanced features capable of enabling additional pathways for energy optimization. As part of this process, systems equipped with bidirectional EVSE functionality were given significant preference, as these systems offer greater potential for energy flexibility and integration with residential energy resources. Following this, the team further prioritized systems that exhibited higher energy efficiency claims and enhanced integration capabilities. The final prioritization rankings, which reflect these criteria, are presented in [Table 3](#).

Table 3: Ranked advanced HEMS.

System Ranking	Advanced HEMS	Reasoning
Highest Priority	AHEMS 1	V2X capabilities with high transmission efficiencies
	AHEMS 3	
Medium Priority	AHEMS 2	High Transmission efficiencies with EVSE, BESS, and PV integration
	AHEMS 4	
	AHEMS 5	
	AHEMS 6	
	AHEMS 8	
Low Priority	AHEMS 7	No PV Support or Unknown Transmission efficiencies
	AHEMS 9	
	AHEMS 10	

Source: CLTC.

Following the product ranking, the team contacted manufacturers to acquire systems, starting with those ranked as highest priority. Some products were unavailable due to backordered inventory,

while one system was determined to be too early in the development stage for assessment. The final systems acquired for testing include models from AHEMS 1, AHEMS 2, AHEMS 3, and AHEMS 4.

Acquired AHEMS

While all test systems operate and provide similar services, there are unique elements to each system’s installation and operational capabilities. AHEMS are often comprised of various components, and each may use a different component integration architecture. The following sections describe the various system access and control methods including system wiring diagrams.

AHEMS 1

AHEMS 1 is the system in the earliest stage of development among those evaluated, and currently exists only as a prototype. Unlike other platforms, AHEMS 1 does not have a first-party battery option and relies exclusively on integration with third-party batteries. Interoperability features are otherwise minimal at this stage of product development. The system’s architecture and wiring configuration are shown in Figure 1.

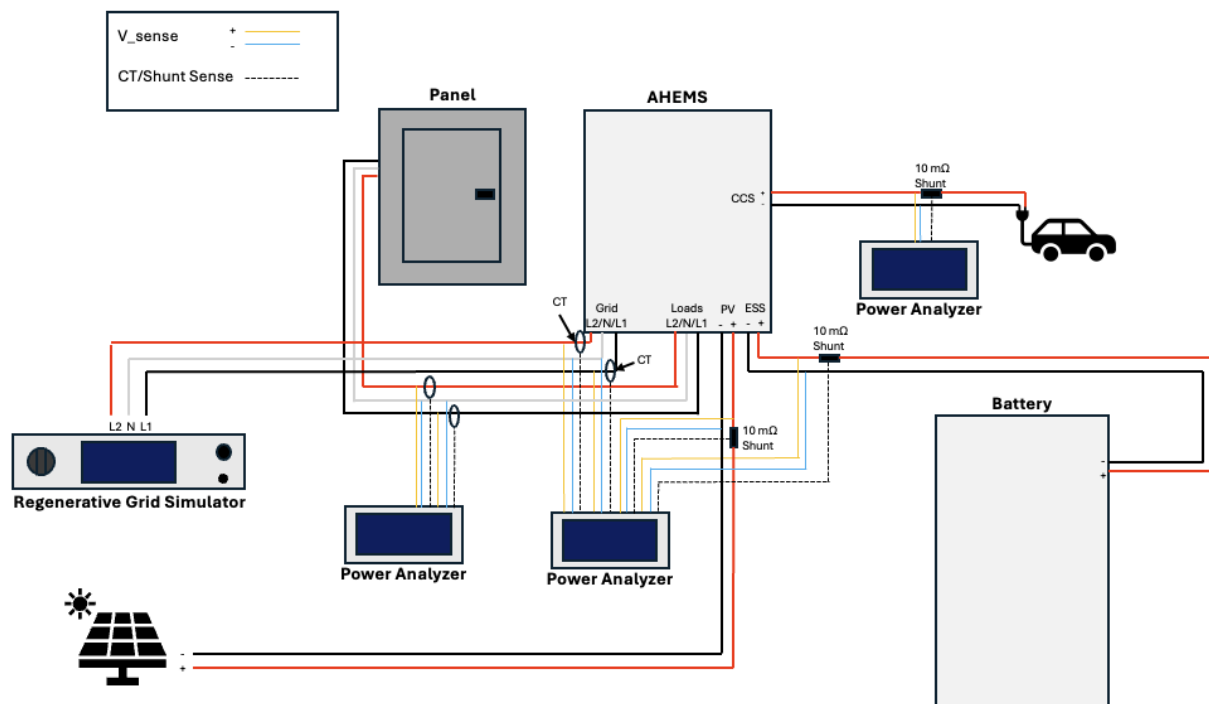


Figure 1. Wiring diagram for AHEMS 1.

Source: CLTC., Manufacturer.

AHEMS 2

AHEMS 2 is a prototype currently under development for the US market. The system consists of two main components, the main unit houses the control logic and provides the connection to the main

panel. A unique feature of AHEMS 2 is that the main unit supports six additional smart loads, separate from the main panel, allowing for enhanced control functionality. The second component is the inverter, positioned on top of the first-party battery. The solar array connects directly to this inverter, and no additional DC options, such as EVSE, are currently supported. Unlike other acquired systems, AHEMS 2 does not have native EVSE options but instead controls an EVSE as it would any other 240-volt load. Interoperability is limited to the manufacturer's own ecosystem, with battery operation limited to first-party products and load controls manipulated via relay triggers. The wiring configuration for the system is illustrated in Figure 2.

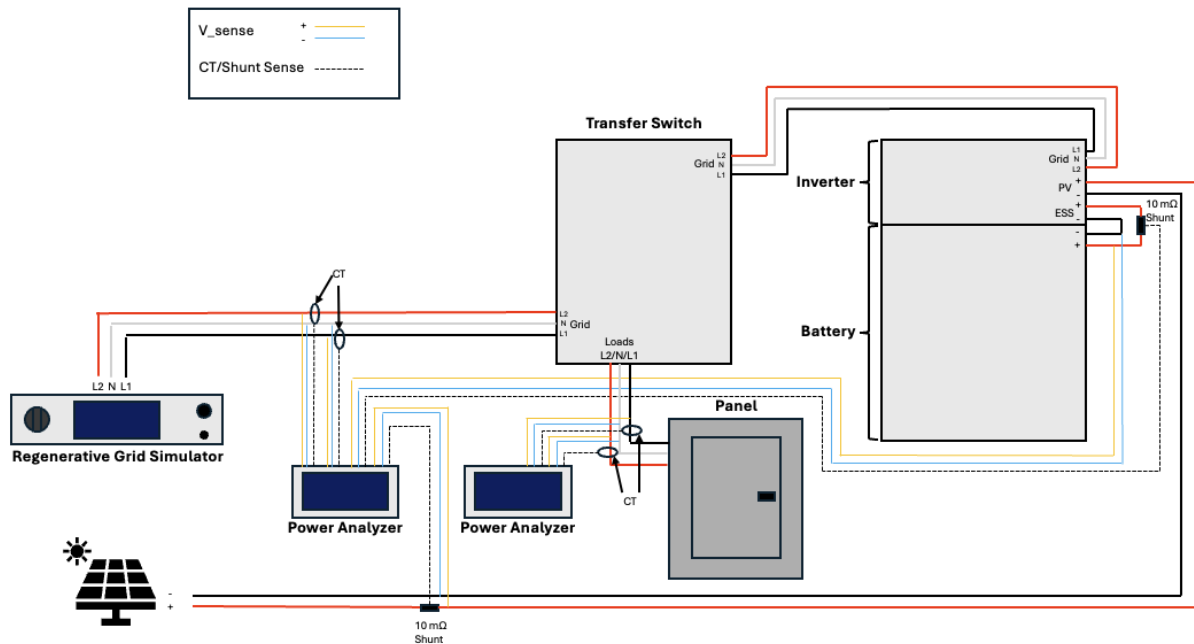


Figure 2: Wiring diagram for AHEMS 2.

Source: CLTC, Manufacturer.

AHEMS 3

AHEMS 3 is composed of five main components, two of which are isolation transformers, which provide protection to the third component, the control hub. The control hub serves as the primary control unit, housing the system logic and connecting to the controlled loads. The fourth component contains the system's black start components, enabling the unit to automatically activate during a power outage. The final component is the system's transfer switch. The company claims interoperability through support for multiple protocols (Ethernet, RS-485) and major EV standards (SAE J1772, CHAdeMO, CCS). Currently, the system operates with third-party batteries, though broader appliance-level interoperability remains limited. The complete wiring specifications are presented in [Figure 3](#).

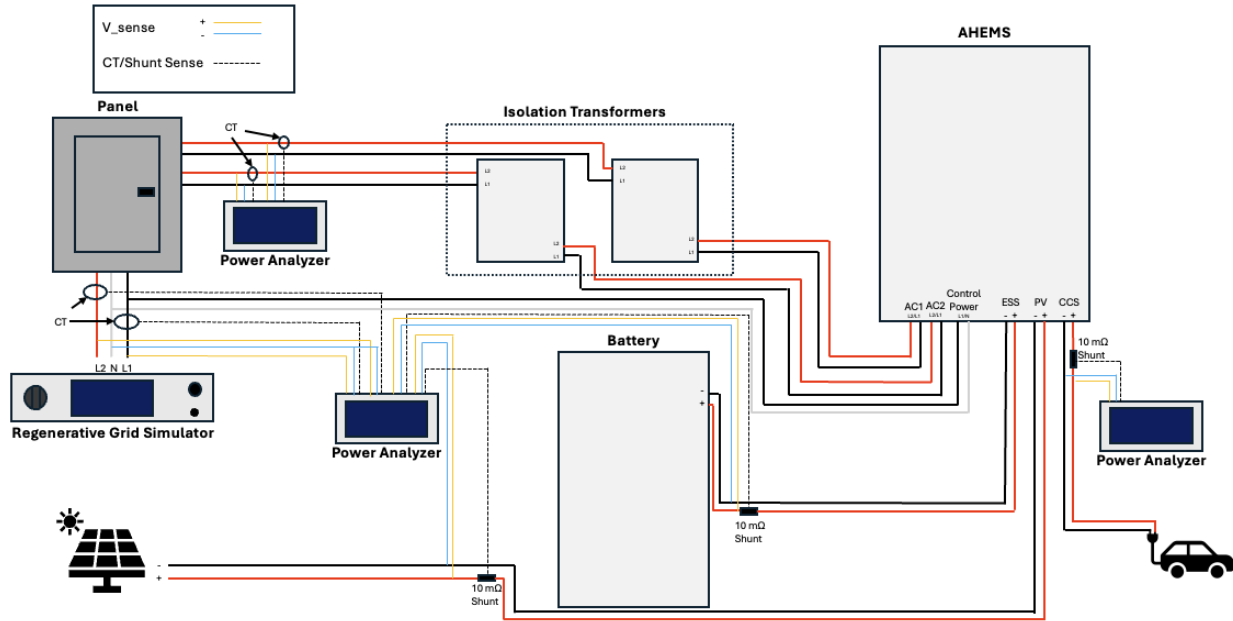


Figure 3. Wiring diagram for AHEMS 3.

Source: CLTC, Manufacturer.

AHEMS 4

AHEMS 4 has been commercially available for the longest length of time among the test systems and consists of two primary components, excluding the battery. The first component is the inverter, which connects to the alternating current (AC) EVSE, the solar array, and the battery. All power transmission-related DC to AC conversions, and vice versa, are managed within the inverter. The inverter also contains the system control logic and connects the system to the cloud.

The second component is the backup piece, which contains the system's black start functionality, allowing the system to function and establish connections during outages, and provides the connection to the main breaker panel. AHEMS 4 ecosystem includes support for first-party batteries as well as certain third-party batteries, but broader smart appliance integration is limited. The corresponding wiring configuration is illustrated in **Figure 4**.

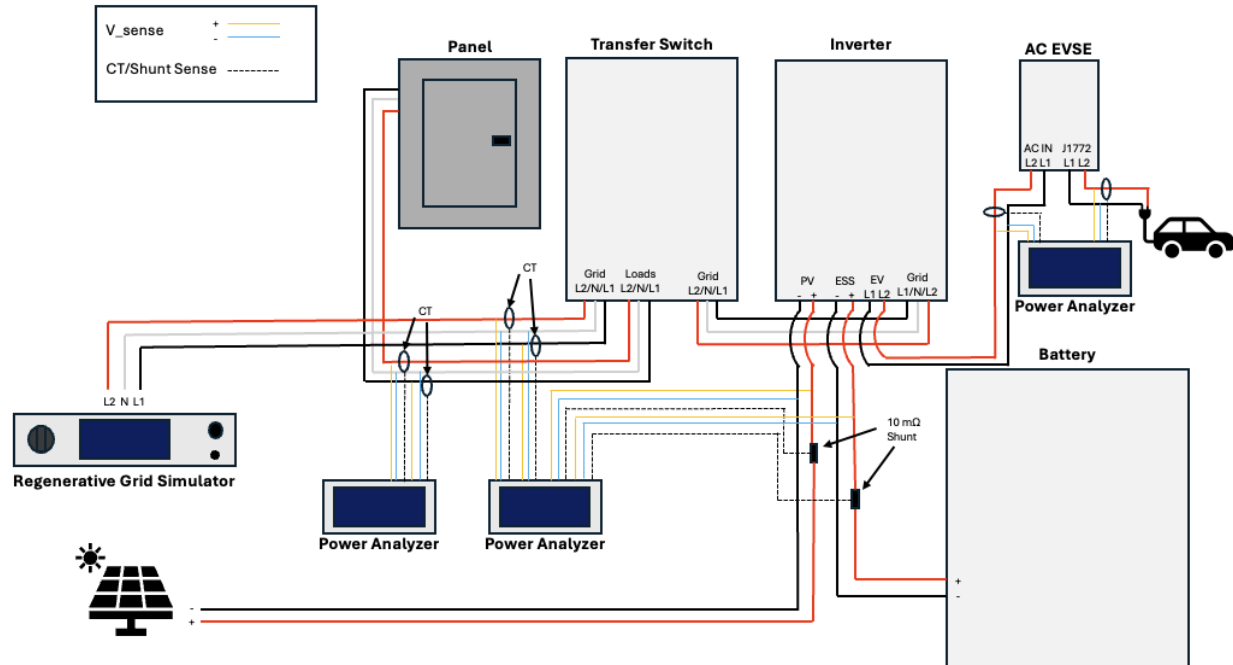


Figure 4. Wiring diagram for AHEMS 4.

Source: CLTC, Manufacturer.

Testing Methodology

The first phase of AHEMS testing involves characterizing the efficiency of each system during a single triggered event for each of the available energy transmission states—such as solar-to-grid, vehicle-to-BESS, etc.—while the second phase focuses on scenario-based evaluations designed to reflect real-world residential use cases. These include conditions such as daily household load cycles, demand response events, EV charging and discharging patterns, and grid outage simulations. Each scenario requires the system to respond dynamically, and the entire daily response is metered to capture overall performance and behavior across multiple events.

Testing Goals

The primary test goals for AHEMS are twofold. First, the objective is to characterize the efficiency of each energy transmission pathway available within the systems and compare them to manufacturer specifications. Second, the team aims to evaluate the systems' responses to various triggers during extended testing periods, providing insights into system behavior and control logic. These triggers will be delivered via a range of system-supported communication protocols, such as API, OpenADR, BACnet, Modbus, and Zigbee.

Energy Throughput Testing

Energy throughput testing will primarily focus on metering the energy entering the first point of contact for the connected AHEMS (input) and the energy delivered to the intended load (output). The

initial test scenarios serve as a starting point for system assessment and may be adjusted based on the specific capabilities of each system.

System Configuration

Due to the uniqueness of each system, individual testing configurations vary slightly, but each follows a similar configuration to the example in [Figure 5](#) below, with the source and sink monitored for each energy transmission pathway under test. Specific probing points for each system are additionally labeled in [Figure 1](#), [Figure 2](#), [Figure 3](#), and [Figure 4](#).

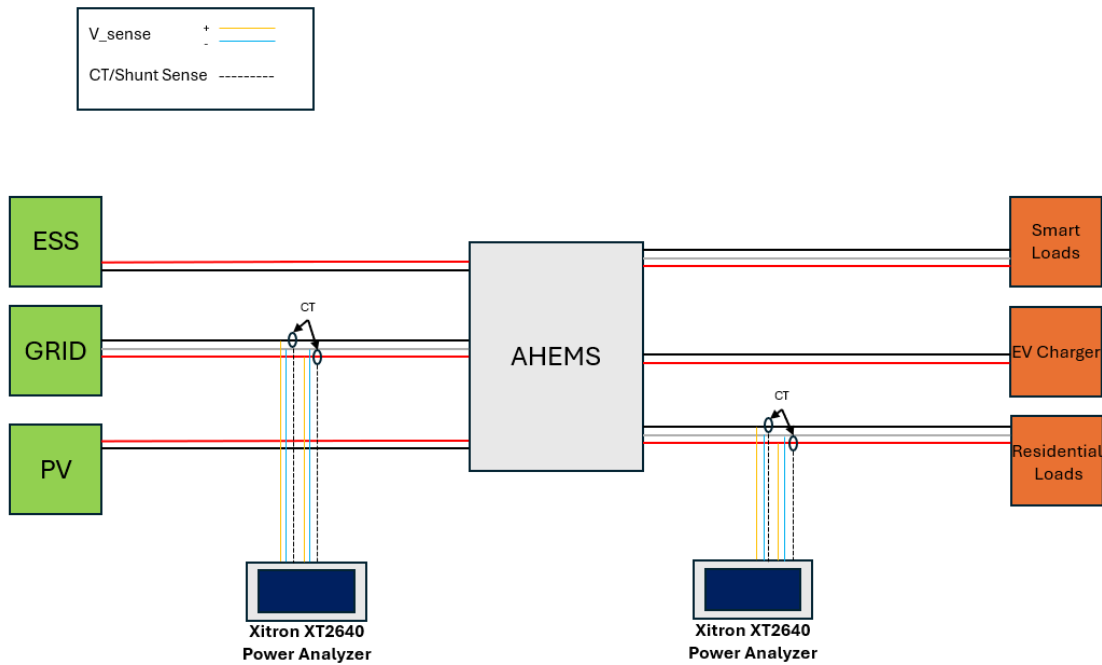


Figure 5: Example system configuration for energy throughput testing (Grid-to-Home).

Source: CLTC.

Testing Scenarios

The testing scenarios are centered around the energy transmission sources and endpoints that the device under test (DUT) can support, as outlined in [Table 4](#). The Input category denotes that the item is functioning as the source of energy transmission, while the Output category signifies that the item is serving as the sink.

Table 4: Scenarios for energy throughput testing.

Scenario	Input (Source)	Output (Sink)
1	Grid	Battery
2	Battery	Grid

Scenario	Input (Source)	Output (Sink)
3	Solar	Battery
4	Solar	Grid
5	Solar	EVSE
6	Battery	EVSE
7	Grid	EVSE
8	EVSE	Grid
9	EVSE	Battery

Source: CLTC.

Testing Procedure

Testing occurs in the following steps:

- 1) Apply power to the DUT(s) through power supply or grid simulator.
- 2) Allow DUT(s) a 30-minute or longer warm-up period.
- 3) Log testing scenario and ensure meters are in the correct position for input and output data recording. If additional equipment needs to be connected or powered, activate it now.
- 4) Begin recording DUT input and output via the power analyzer.
- 5) Set DUT to activate power transmission for at minimum one hour and log start time.
- 6) After test is over, log end time.
- 7) Repeat steps three through six for each scenario. If a new scenario requires new power lines to be established, deenergize testbed and start from step one after modifications have been made.
- 8) De-energize the DUT and stop recording power once scenarios of interest are tested.

Event Response Testing

Event response testing was conducted to evaluate system performance under conditions representative of a typical residential operating day. The intent was to observe how each advanced HEMS managed household load fluctuations, responded to Time-of-Use (TOU) pricing, and integrated solar and battery resources in real time.

Each system was subjected to a 24-hour operating profile modeled on a single-family dwelling from the Residential Appliance Saturation Survey (RASS). The profile included three load levels—low, medium, and high—reflecting daily demand cycles. The team simulated these loads through a series of resistive elements connected to the AHEMS unit, scaled to reproduce the hour-by-hour demand from the RASS dataset.

In parallel, the team incorporated solar input and battery cycling to simulate DERs behavior. Depending on system capabilities, solar power input was provided either through a DC power supply designed to simulate PV or through an actual PV panel array. Battery operation was scheduled to align with TOU optimization, enabling the team to evaluate the systems' ability to prioritize load shifting and resource dispatch under dynamic conditions.

System Configuration

The system configuration for event response testing is similar to that used for energy throughput testing, with the addition of voltage and current monitoring at multiple points to enable comprehensive capture of system energy transmission. This approach ensures a detailed assessment system energy management during various events. The general system wiring diagram is presented in [Figure 6](#).

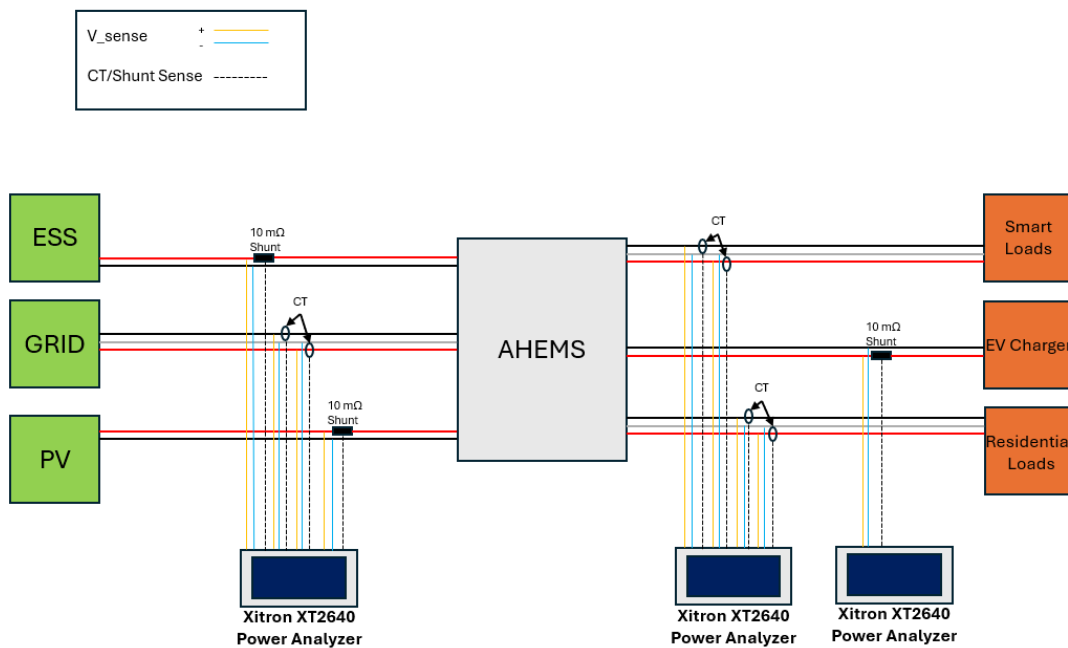


Figure 6: System configuration for event response testing.

Source: CLTC.

The event response testing was carried out using a 24-hour residential load profile representative of a typical single-family dwelling. This profile was derived from the RASS single-family dwelling dataset, as shown in [Figure 7](#), and applied through a series of resistive loads connected to the AHEMS unit. (DNV GL Energy Insights USA 2021)

The RASS-based profile looked at varying demand levels across the day, including morning, afternoon, and evening peaks. In testing, these load conditions were simulated by scaling resistive loads to match the hour-by-hour energy consumption values from the dataset. This allowed for consistent, repeatable testing of each system's response to household demand fluctuations, in combination with solar input and TOU pricing signals.

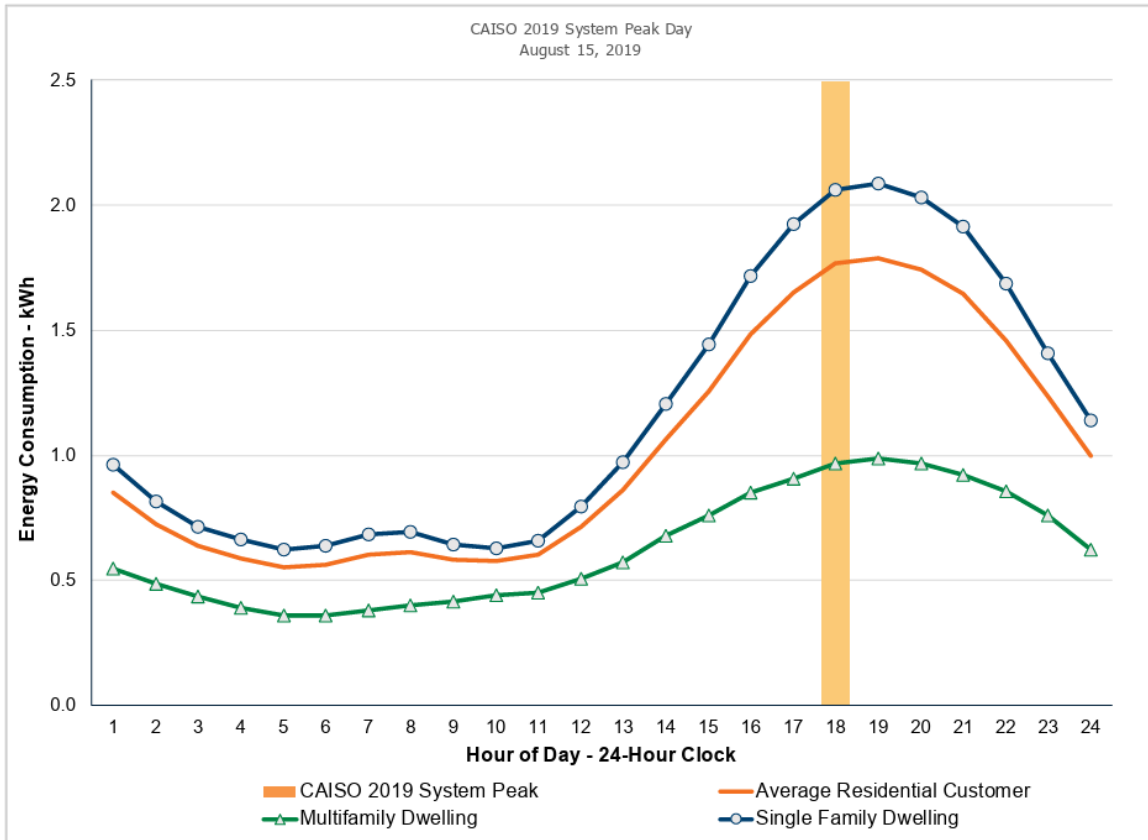


Figure 7: Single-family and multifamily load profiles.

Source: RASS

Testing Scenarios

Table 5 provides an initial list of testing scenarios, and in the events section, outlines the change of states that the advanced HEMS will experience during a day profile. If deemed necessary, AHEMS with V2G and V2B functionality will undergo additional discharging events.

Table 5: Testing scenarios for event response testing.

Scenario	Events
1	Load increase from low to medium; TOU pricing applied; solar generation active; battery available. Dischargeable EV available (if applicable).
2	Load increase from medium to high; TOU pricing applied; solar generation active; battery available. Dischargeable EV available (if applicable).
3	Load decrease from high to medium; TOU pricing applied; solar generation active; battery available. Dischargeable EV available (if applicable).

Scenario	Events
4	Load decrease from medium to low; TOU pricing applied; solar generation active; battery available. Dischargeable EV available (if applicable).
5	Grid outage simulated with solar generation and battery available.

Source: CLTC.

Testing Procedure

Testing should be set up at least an hour prior to the event start time to ensure the AHEMS can process a proper response is set in time:

- 1) Apply power to the DUT(s) through power supply or grid simulator.
- 2) Allow DUT(s) a 30-minute or longer warm-up period.
- 3) Log testing scenario(s) and ensure meters are in the correct position for recording all relevant parameters for event triggers. If additional equipment needs to be connected or powered, activate now.
- 4) Begin recording DUT via the power analyzer.
- 5) Set scenario(s) via DUT software or through connection to local machine or API.
- 6) Set DUT to respond and log start time.
- 7) After scenario(s) are over, log end time.
- 8) De-energize the DUT and stop recording power.

Testbed Development

To implement the testing methodology, the team designed and configured a testbed capable of monitoring and controlling connected resources for the various devices under test (DUTs) through a simplified control box. This control box interfaces directly with a set of AC and DC relays, enabling simple switching between configurations. It operates on an Arduino Mega, with configuration commands initiated through a series of push buttons, each of which activates a corresponding LED to indicate active selections. For safety and accuracy, the system only permits configuration changes during idle power conditions when the DUTs are not drawing current, and it automatically locks out modifications if it detects power flow to a load. Control system specifications are shown in [Table 6](#), while wiring specifications for the control box (Figure 8) are included in [Appendix A](#).



Figure 8: Advanced HEMS control box in the CLTC laboratory.

Source: CLTC.

Table 6: Testbed control components.

Component	Manufacturer	Specifications
AC Relay	Durakool	Solid State Relay, Single-phase, SPST-NO, 80 A, 240 VAC, Panel Mount, Screw, Zero Crossing
AC CT	Magnelab	DCT-0010 5 Vdc Output AC Current Transducers by Magnelab
DC Contactor	Littelfuse	Contactors - Electromechanical 100A 750V 12V COIL BM NP
DC CT	Aim Dynamics	AIMH021-5V Series Hall Effect Current Transducers ± 5 V Output by Aim Dynamics
DC Shunt	Ohmite	Current Sense Resistors - Through Hole 100W .0100 ohm 0.5% Four Terminals
Microcontroller	DFRobot	Development Boards & Kits - AVR Arduino Mega 2560 Rev3

Source: CLTC.

Power Supply

The testbed is connected to a Chroma 61815 grid simulator instead of a traditional power supply, which allows the team to evaluate discharging features in a controlled and regulated environment. The Chroma 61815 offers full four-quadrant, regenerative capabilities, allowing it to absorb energy from the DUT and return it to the grid—and enhance test efficiency. It also supports both single-phase and three-phase output modes, providing flexibility to accommodate diverse testing requirements. Detailed accuracy specifications of the Chroma 61815 are provided in the separate [Appendix B](#) equipment specification document, available upon request.

Power Analyzer

The power analyzers used for testing are Xitron XT2640-4CH and Xitron 2802 units, which support the use of various internal and external current monitoring methods. This also enables comprehensive monitoring of the system’s performance across AC and DC electrical architecture. The Xitron units are high-precision, multi-channel power analyzers that exceed revenue-grade accuracy metering requirements, making them well-suited for detailed AHEMS assessments. Minimum specifications for the Xitron power analyzers are provided in [Table 7](#) and [Appendix B](#).

Table 7: Minimum accuracy specifications for power analyzers.

Specification	Accuracy
Voltage	0.2%
Current	0.2%
Power	0.08%

Source: CLTC.

Testbed Loads

While the testbed is connected to a variety of real loads—such as a solar array, BESS, EVSE and home appliances—it also fully supports simulated AC and DC loads. DC load simulation is facilitated by two Chroma 62120D-600 bidirectional DC power supplies, which also enables the simulation of solar input, DC electric vehicles, and batteries. The solar simulation feature is particularly unique, as it allows for precise control of solar input characteristics, offering an accurate emulation of real-world solar conditions. System specifications for the Chroma 62120D-600 are detailed in [Appendix B](#).

Results

The following section presents the results of this project’s laboratory testing, divided into two parts: energy throughput performance, and trigger response behavior. This structure allows for a consistent comparison of capabilities across systems while highlighting both efficiency outcomes and operational stability.

Energy Throughput Results

The team conducted energy throughput testing only for pathways applicable to each system’s capabilities. As a result, scenarios such as vehicle-to-home (V2H) operation were not evaluated for systems without bidirectional or EVSE functionality.

In addition, the team performed battery-related throughput testing (grid-to-battery charging and battery-to-grid discharging) as full-cycle tests rather than one-hour intervals. This approach captures the complete efficiency profile, including losses associated with changes in battery state of charge (SOC), and provides a more accurate assessment of system performance over the entire usable capacity.

AHEMS 2 Results

Testing of the AHEMS 2 showed consistently high efficiency across all major energy pathways, with results generally falling between 90 and 94 percent. Solar-to-battery and solar-to-grid pathways both operated above 92 percent, reflecting strong DC-to-DC conversion performance. Battery-to-grid discharge and grid-to-battery charge cycles also delivered efficiencies close to or exceeding 90 percent, with the highest observed during grid charging at just over 94 percent. Efficiencies per use case can be viewed in [Table 8](#).

Table 8: Throughput efficiencies for AHEMS 2 pathways.

Scenario	Source Avg (W)	Sink Avg (W)	Throughput Efficiency
Grid to Battery	7375.95	6941.34	94.11%
Battery to Grid	7831.34	7068.85	90.26%
Solar to Battery	1254.22	1160.86	92.56%
Solar to Grid	2015.28	1877.46	93.16%

Source: CLTC

These results indicate that the AHEMS 2 platform is well-optimized for core residential use cases. Performance did not vary dramatically between modes, suggesting that its conversion architecture is broadly effective across different transmission states. From a practical standpoint, this means end users can expect relatively uniform efficiency regardless of whether the system is prioritizing solar utilization, storage cycling, or export to the grid.

The stability of input and output power flows varied more widely than efficiency values, reflecting differences in source characteristics. Grid-related pathways, including both charging and discharging of the battery, demonstrated excellent stability with coefficients of variation (CV) in the 2 to 4 range. These results suggest highly predictable performance when operating from grid inputs or delivering directly back to the grid.

Table 9: Stability of AHEMS 2 testing.

Scenario	Source Standard Deviation	Source Coefficient of Variation	Sink Standard Deviation	Sink Coefficient of Variation
Grid to Battery	195.56	2.65	178.32	2.57
Battery to Grid	341.39	4.36	303.23	4.29
Solar to Battery	222.42	17.73	212.82	18.33
Solar to Grid	98.49	4.89	92.36	4.92

Source: CLTC

Solar-driven pathways showed greater variability. Solar-to-battery testing recorded CV values above 17 for both source and sink power, while solar-to-grid operation was moderately variable at around 5. This reflects the inherent intermittency of solar generation and highlights the importance of storage integration in smoothing power delivery. Overall, the system combines high efficiency with stable operation in grid-related modes, while solar pathways remain subject to expected fluctuations.

Table 10: Runtime deltas of AHEMS 2 testing.

Scenario	Source Power – Starting Avg (W)	Source Power – Stopping Avg (W)	Sink Power – Starting Avg (W)	Sink Power – Stopping Avg (W)	Efficiency – Starting Avg (%)	Efficiency – Stopping Avg (%)
Grid to Battery	7401.75	7157.55	6964.60	6745.66	94.09	94.27
Battery to Grid	8148.29	7323.67	7369.99	6615.97	90.45	90.34
Solar to Battery	998.64	1625.04	915.88	1515.16	91.71	93.24
Solar to Grid	1768.72	2096.07	1645.17	1952.89	93.02	93.17

Source: CLTC

Time-series analysis shows that the system maintained stable or slightly improving efficiencies across both short-duration and full-cycle tests. For the hour-long solar pathways (solar-to-battery and solar-to-grid), efficiency increased modestly over time. Solar-to-battery rose from 91.7 percent in the first 10 percent of the run to 93.2 percent in the final 10 percent, while solar-to-grid improved from 93 percent to 93.2 percent. These trends suggest that solar-driven operation benefits from system stabilization as input conditions and regulation settle.

For the full charge and full discharge battery cycles, efficiency remained very consistent. Grid-to-battery charging improved slightly from 94.1 to 94.3 percent, while battery-to-grid discharge dipped only marginally from 90.5 percent to 90.3 percent.

AHEMS 4

AHEMS 4 displayed a wider spread of efficiency values across use cases, ranging from approximately 94 percent to nearly 99 percent. The strongest results were achieved in grid-to-battery charging, which approached perfect efficiency, and in battery discharge to the grid, which also performed above 95 percent. Solar-to-battery efficiency was likewise strong at just over 97 percent, and solar-to-grid functionality was just under 95 percent. Efficiency values are available in [Table 11](#).

Table 11: Throughput efficiencies for AHEMS 4 pathways.

Scenario	Source Avg (W)	Sink Avg (W)	Throughput Efficiency
Grid to Battery	4978.66	4936.71	99.16
Battery to Grid	5010.88	4807.36	95.94
Solar to Battery	1944.30	1893.05	97.36
Solar to Grid	1443.21	1367.00	94.72

Source: CLTC

Stability testing revealed significant differences across pathways. Battery discharge to the grid was exceptionally stable, with CV values below 1 for both input and output power, demonstrating precise control and predictable operation. Grid-to-battery charging also performed well, with CV values around 4, indicative of reliable throughput.

Table 12: Stability of AHEMS 4 testing.

Scenario	Source Standard Deviation	Source Coefficient of Variation	Sink Standard Deviation	Sink Coefficient of Variation
Grid to Battery	201.10	4.04	199.93	4.05
Battery to Grid	24.26	0.48	23.46	0.49
Solar to Battery	6.69	0.34	196.19	10.36
Solar to Grid	125.79	8.72	122.33	8.95

Source: CLTC

Solar-related pathways exhibited higher variability. Solar to battery charging showed very stable input power (CV < 1) but more variable output delivery (CV ~10), suggesting that while solar harvesting is steady, downstream regulation introduces fluctuations. Solar-to-grid conversion was more variable than the battery pathway, with input and output CV values near 9.

Table 13: Runtime delta of AHEMS 4 testing.

Scenario	Source Power – Starting Avg (W)	Source Power – Stopping Avg (W)	Sink Power – Starting Avg (W)	Sink Power – Stopping Avg (W)	Efficiency – Starting Avg (%)	Efficiency – Stopping Avg (%)
Grid to Battery	4900.57	4989.51	4858.93	4947.35	99.12	99.16
Battery to Grid	5015.76	5005.87	4812.42	4802.70	95.95	95.94
Solar to Battery	1936.21	1939.70	1885.21	1887.62	97.37	97.31
Solar to Grid	1237.63	1618.91	1167.08	1537.81	94.30	94.99

Source: CLTC

The system exhibited pathway-dependent efficiency behavior over time, with performance stability tied closely to the type of energy flow. For the hour-long solar pathways, results diverged slightly. Solar-to-battery efficiency held steady at 97.3 percent throughout the test, confirming consistent and stable DC-to-DC conversion. In contrast, solar-to-grid efficiency averaged between 94 and 95 percent, demonstrating the highest variance but remaining fairly consistent.

For the full-cycle battery tests, both grid-to-battery charging and battery-to-grid discharging maintained excellent performance. Charging efficiency remained at 99.2 percent from start to finish, while discharging efficiency averaged 95.9 percent with no meaningful decline over the full cycle. These results confirm that the system performs strongly in grid-integrated battery operations—and that efficiency is not significantly impacted by changes in battery state of charge.

AHEMS 1

AHEMS 1 was delivered to the research team as an early-stage prototype, provided in place of a production unit due to delays in the manufacturer’s development timeline. Upon arrival, the unit was found to have sustained significant shipping damage, including multiple broken capacitors and severed connections between printed circuit boards.

Because of this damage, the system could not be powered on or evaluated under laboratory conditions. The research team is currently coordinating with the manufacturer to facilitate repairs and restore the unit to working order. However, at the time of this report, no assessment of throughput efficiency or stability has been possible.

AHEMS 3

The research team received the system, but it was not fully functional for laboratory testing during the reporting period. While the unit could be powered on and accessed through its interface, hardware and software limitations prevented evaluation of its energy throughput capabilities. As a result, quantitative efficiency or stability results could not be obtained.

Trigger Response Results

Event response testing evaluated how each system managed a dynamic 24-hour residential operating profile under conditions representative of a typical single-family dwelling. The test design incorporated staged load increases and decreases—low to medium, medium to high, high to medium, and medium to low—while solar generation remained active throughout and TOU pricing signals were applied continuously. The goal was to observe how each AHEMS prioritized solar, battery, and grid interactions while maintaining household load support and optimizing for TOU conditions. In addition, each system was subjected to a grid outage scenario to assess backup response capabilities.

AHEMS 2

Testing of the AHEMS 2 system was conducted over a 24-hour test profile, running from 12:00 p.m. on day one to 12:00 p.m. the following day. For this evaluation, the system’s battery work mode was set to TOU. The system provides three pre-programmed TOU rate profiles corresponding to the major California IOUs:

- Pacific Gas & Electric (PG&E) – E-ELEC-NEM3.0
- Southern California Edison (SCE) – TOU-D-PRIME-NEM3.0
- San Diego Gas and Electric (SDGE) – EV-TOU-5-NEM3.0

For this testing, the team selected the PGE E-ELEC-NEM3.0 schedule; the applicable rate structure is shown in [Figure 9](#). In addition, there is a daily base service charge of \$0.49. Seasonal differentiation applies, with summer rates active from June 1 to September 30 and winter rates active from October 1 to May 31 (PGE n.d.).

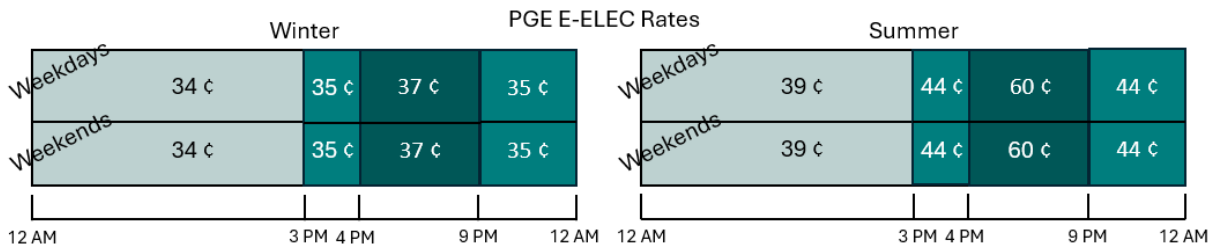


Figure 9: PGE E-ELEC rate structure.

Source: PGE

The TOU schedule is non-adjustable and follows the fixed behavior pattern below:

- 00:00 – 15:00: Allow Charging
- 15:00 – 16:00: Self-Use (prioritize solar and battery for loads)
- 16:00 – 21:00: Maximize Discharge to Grid (until minimum SOC of 10%)

- 21:00 – 23:59: Self-Use

System performance under this schedule is illustrated in [Figure 10](#), which shows grid power flows with the overlaid TOU pricing rates. At the onset of the peak period (4:00 p.m.), the system immediately initiated discharge to the grid at its rated output, continuing until the minimum SOC threshold was reached. Once the off-peak period began at 12:00 a.m., the battery recharged fully, ensuring capacity for the next day. While this strategy might maximize bill savings, it did not maintain reserve capacity, leaving the system without backup energy in the event of an outage occurring after the scheduled discharge.

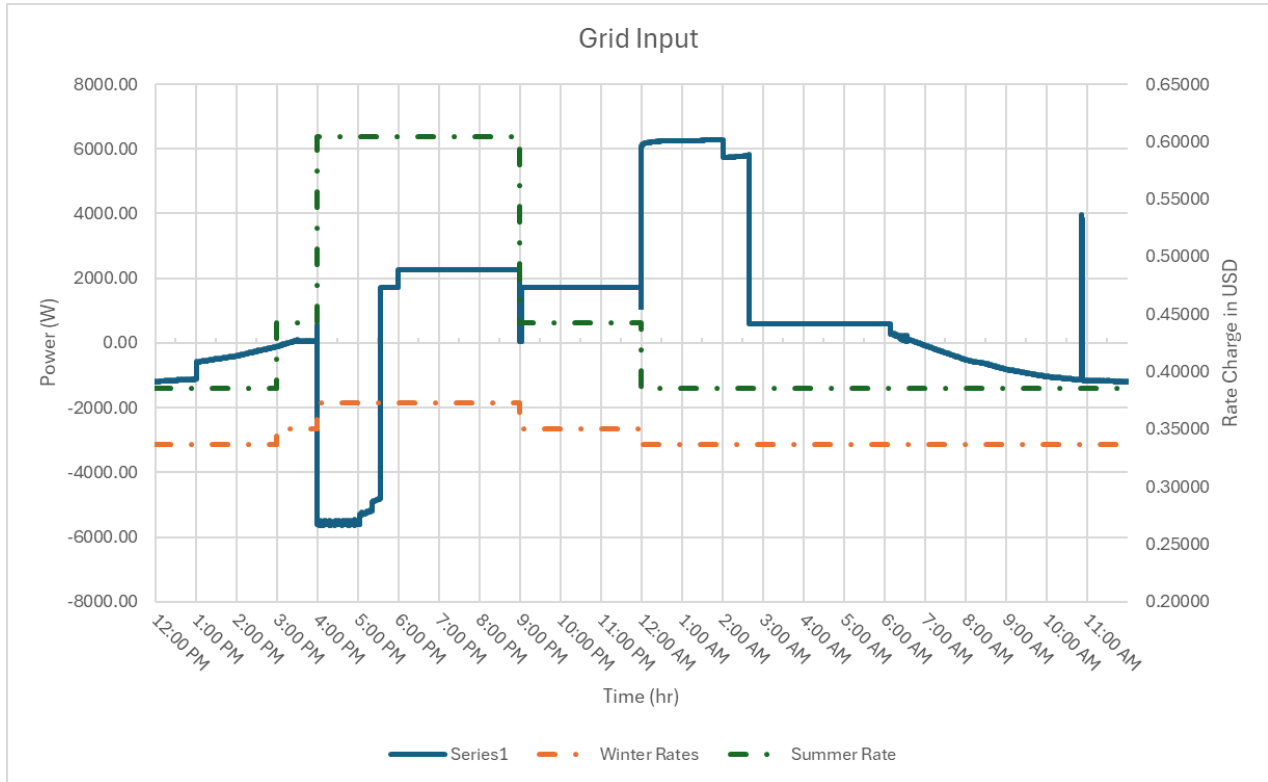


Figure 10: Grid response from AHEMS 2 event trigger testing.

Source: CLTC

[Figure 11](#) further displays the contributions of battery input, solar input, and load output at the AHEMS system level. These results show that mid-day solar generation was consistently exported to the grid rather than stored, since the battery had already been fully charged overnight. Minor anomalies were also observed, with brief charging and discharging events around 9:00 p.m. and 11:00 a.m. that did not align with the defined control strategy.

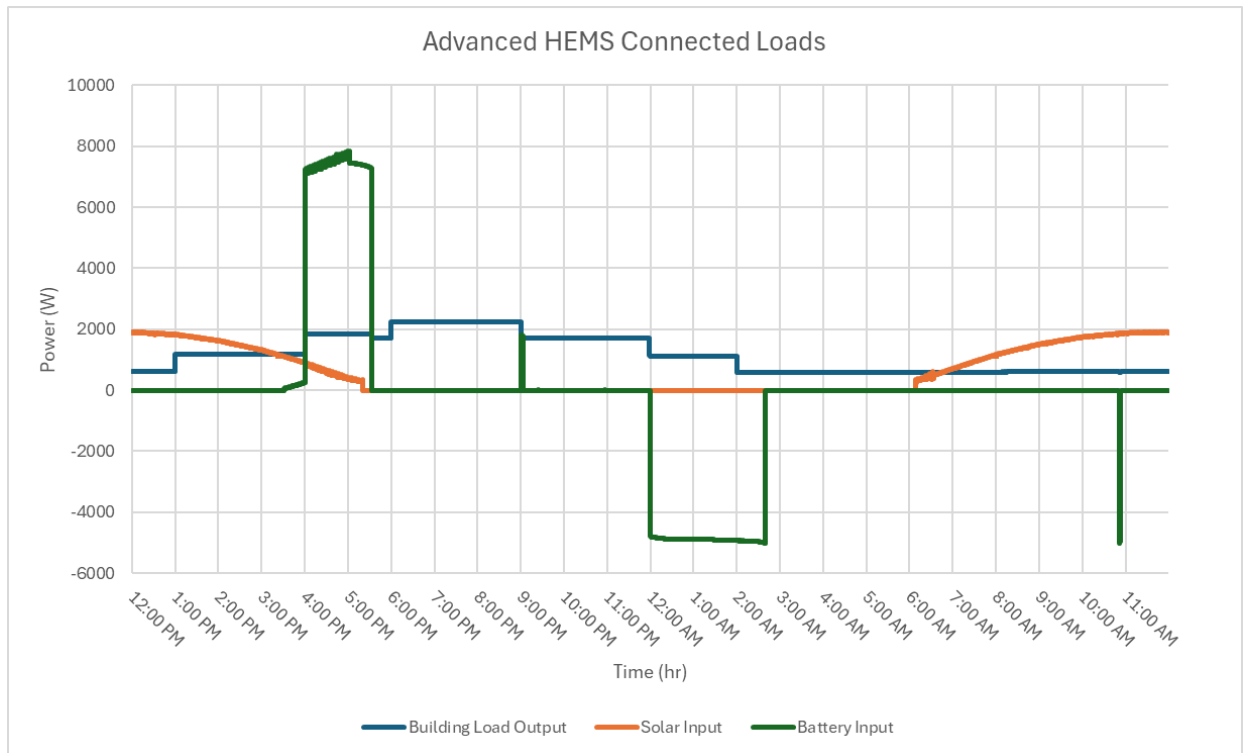


Figure 11: Connected loads to AHEMS 2 during event trigger testing.

Source: CLTC

Overall, the system followed its pre-programmed TOU work mode accurately, demonstrating reliable compliance with tariff-based dispatch schedules. However, the fixed nature of the strategy highlights a trade-off between rate optimization and resiliency, as the system does not preserve energy reserves once a full discharge has occurred.

AHEMS 4

AHEMS 4 was configured with a slightly different setup than AHEMS 2 due to differences in commissioning requirements. Similar to AHEMS 2, the system offered Time-of-Use (TOU) rate presets; however, AHEMS 4 uniquely allowed separate selection of import and export tariffs. Although this feature suggests flexibility, no practical use cases were identified where mismatched import/export rates provided benefit.

The available import rates included:

- PG&E E-ELEC
- SCE TOU-D-PRIME

Export rate options were:

- PG&E NEM 3.0
- SDGE NEM 3.0

- SCE NEM 3.0

While SDGE appeared as an import option, its rate fields failed to populate any data, indicating a probable software defect. For testing, the team selected PG&E E-ELEC as the import rate and PG&E NEM 3.0 as the export rate. The applied rate structures matched those shown in Figure 9.

In contrast to AHEMS 2, AHEMS 4 did not provide any transparency into the underlying dispatch logic for charging and discharging during TOU operation. Test results revealed unintuitive grid interaction. As shown in Figure 12, several hours after TOU mode initiation, the system initiated battery discharge during off-peak periods, when discharge would offer no economic advantage. After nearly full discharge, the system immediately began charging, only to discharge again shortly thereafter. A second prolonged charging period extended into partial-peak and peak windows.

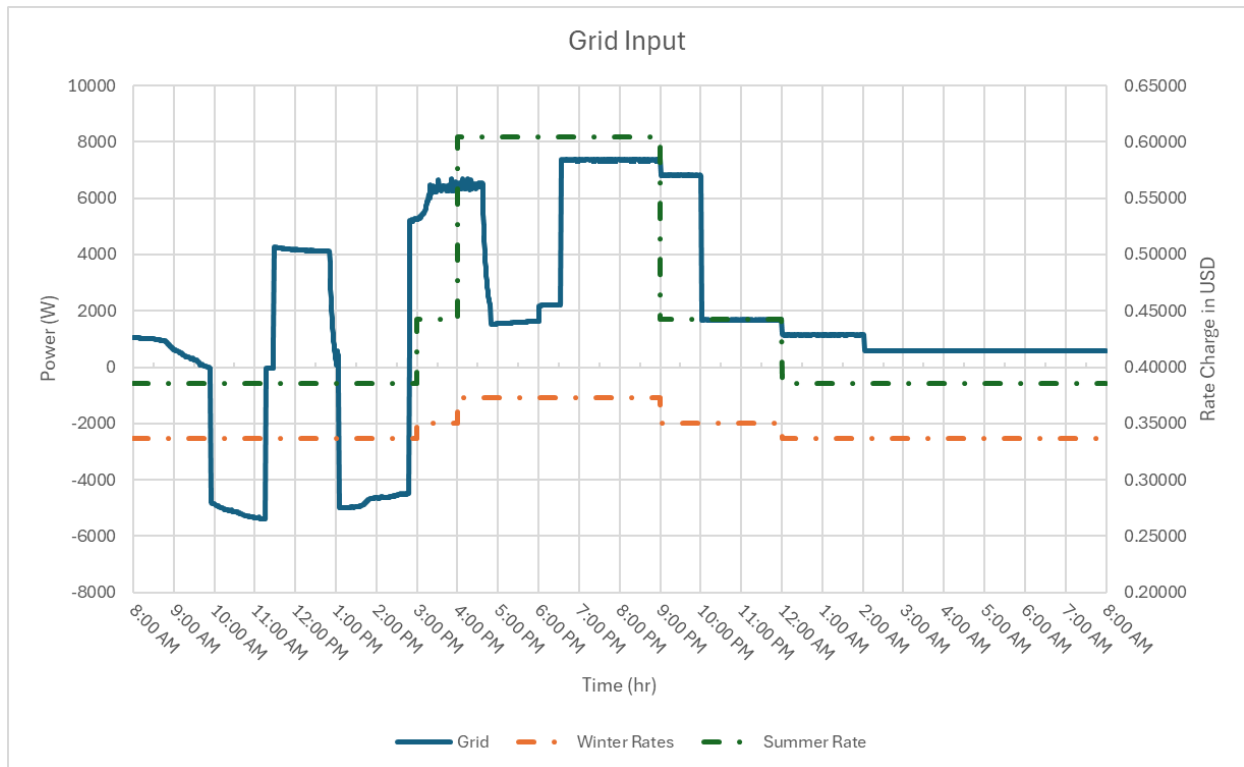


Figure 12. Grid response from AHEMS 4 event trigger testing.

Source: CLTC

Once the battery reached full state of charge, it remained idle for the remainder of the test. Additionally, EVSE charging began to occur around 6:30 PM instead of during the off-peak period starting at 12 AM. Battery, solar, and load profiles are shown in Figure 13.

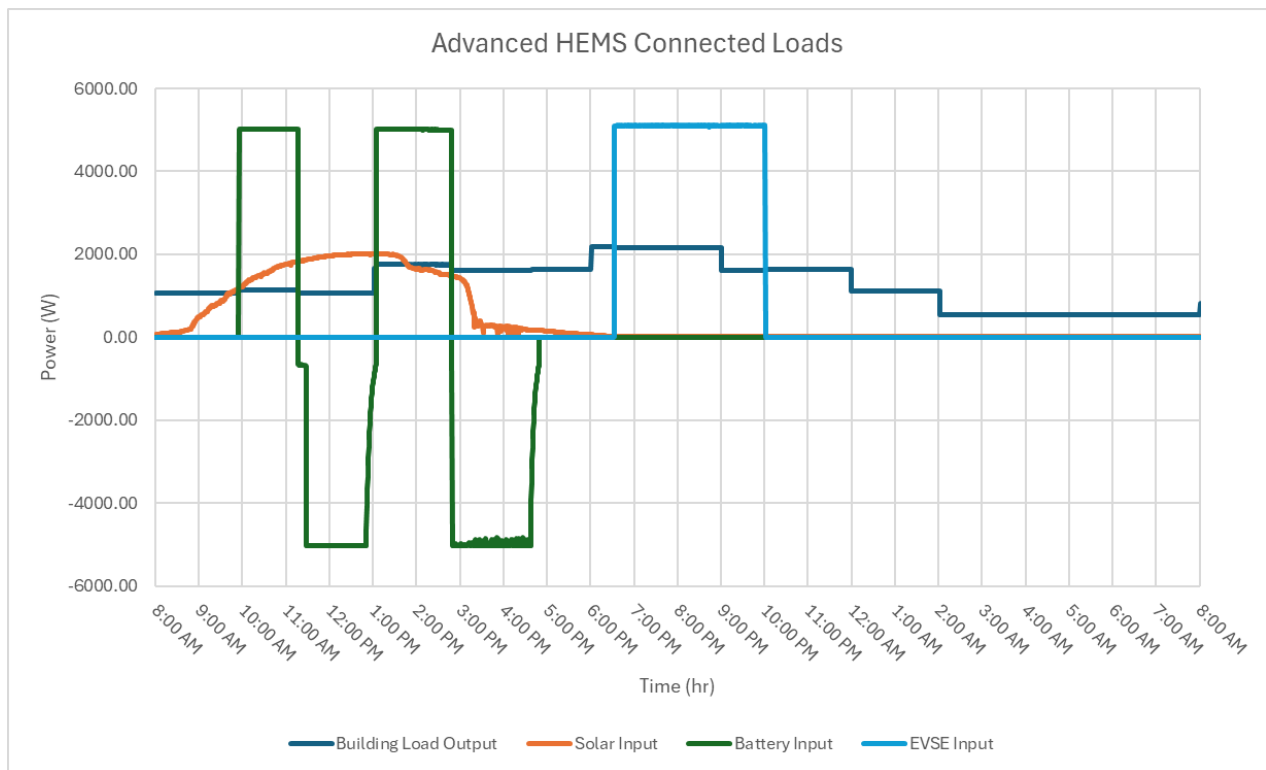


Figure 13. Connected loads to AHEMS 4 during event trigger testing.

Source: CLTC

To investigate configuration errors, multiple operating settings were adjusted. Despite these efforts, AHEMS 4 consistently demonstrated non-optimal behavior under all TOU configurations. Initial testing used the system’s first-party battery; follow-up testing with a third-party battery produced similarly unexpected results. In one case, although discharge was initiated at 7:00 p.m., the system never allocated time for charging, leaving the battery depleted for the duration of the test.

Overall, AHEMS 4’s TOU functionality appeared underdeveloped for cost optimization. Although this model is a fully released commercial product, issues such as missing TOU datasets, lack of dispatch transparency, and counterproductive battery usage indicate it is not yet capable of delivering reliable TOU-based savings in real-world conditions. That said, outside of TOU mode, users can manually define fixed charge/discharge schedules, suggesting that technically proficient users may still achieve savings through custom programming.

Analysis

Across the tested pathways, both AHEMS 2 and 4 demonstrated generally high efficiencies, though the performance profiles were distinct. AHEMS 2’s measured values consistently clustered between 90 and 94 percent, with only minor variation across pathways. This indicates a well-balanced conversion architecture, where performance is relatively uniform regardless of whether the system is charging from the grid, discharging to the grid, or cycling solar energy through storage.

AHEMS 4 displayed a similar spread though overall slightly higher efficiencies, ranging from 95 percent to over 99 percent, reflecting strong but still pathway-dependent performance. Battery-related operations, both charging and discharging, delivered efficiencies at or above 95 percent, aligning with expectations for a mature storage-integrated platform. Solar-to-battery charging was equally robust at approximately 97 percent, while solar-to-grid export averaged approximately 95 percent, placing all conversion modes within a high and relatively narrow efficiency band.

Claimed efficiencies for AHEMS 2 were uniform at 96 percent across all pathways. Measured values fell modestly below this figure, ranging from 90 to 94 percent. By contrast, AHEMS 4’s claimed efficiencies varied by pathway, with 94.5 percent for battery-related flows and 99 percent for solar-to-grid. Measured results generally confirmed or exceeded these claims for grid charging, discharging, and solar-to-battery operation, while solar-to-grid export—though highly efficient at approximately 95 percent—was below the manufacturer’s stated value.

Table 14: Claimed efficiency vs. measured efficiency—AHEMS 2.

AHEMS 2	Manufacturer Claimed Efficiency	Tested Efficiency
Grid to Battery	96.00%	94.11%
Battery to Grid	96.00%	90.26%
Solar to Battery	96.00%	92.56%
Solar to Grid	96.00%	93.16%

Source: CLTC

Table 15: Claimed efficiency vs. measured efficiency—AHEMS 4.

AHEMS 4	Manufacturer Claimed Efficiency	Tested Efficiency
Grid to Battery	94.50%	99.16%
Battery to Grid	94.50%	95.94%
Solar to Battery	94.50%	97.36%
Solar to Grid	99.00%	94.72%

Source: CLTC

In addition to efficiency, stability results reinforced these patterns. Both systems performed most reliably in grid-related pathways, with coefficients of variation typically below 5, reflecting predictable, repeatable throughput. Solar-driven pathways, however, exhibited greater variability. AHEMS 2 showed higher variability in solar-to-battery testing (CV ~18), suggesting fluctuations in downstream regulation when charging storage from PV. In contrast, AHEMS 4’s solar-to-grid pathway displayed more variability than its battery-related flows (CV ~9), indicating more sensitivity. These results underscore that while both platforms maintain high efficiency across modes, stability characteristics overall increase in solar-driven scenarios.

In event trigger testing, researchers found that AHEMS 2 operated reliably according to its fixed TOU work mode, dispatching energy in alignment with the PGE E-ELEC-NEM3.0 tariff structure. The unit discharged fully to the grid during the designated peak period (4:00 p.m. to 9:00 p.m.) and recharged overnight, while mid-day solar generation was primarily exported to the grid rather than stored. This behavior maximized bill savings under the selected rate schedule but left no reserve capacity in the event of an outage following peak discharge.

To evaluate the economic impact of this control logic, daily import costs and export savings were calculated by applying the PG&E TOU rates directly to the grid meter data. Grid imports were multiplied by the applicable TOU price to determine daily energy cost, while exports were multiplied by the same rate to estimate daily energy savings. In this context, “daily energy savings” refers specifically to the monetary value of energy exported back to the grid, not on-site consumption reduction. Savings can therefore exceed costs when the system exports more kilowatt-hours than it imports, particularly during high-value peak periods. This results in a net positive daily balance under retail-rate assumptions, as shown in [Table 16](#).

Table 16: Daily energy cost and savings of AHEMS 2.

AHEMS 2	Daily Energy Cost	Daily Energy Savings	Daily Net Benefit
Winter Season	\$ 10.87	\$ 14.90	\$ 4.03
Summer Season	\$ 14.00	\$ 19.69	\$ 5.69

Source: CLTC

When extrapolated across the year (243 winter days, 122 summer days) in line with the PG&E seasonal breakdown, these values produced:

- **Winter:** \$2,643 cost vs. \$3,620 savings, resulting in net ~\$977 benefit
- **Summer:** \$1,708 cost vs. \$2,402 savings, resulting in net ~\$694 benefit
- **Annual total before service charge:** ~\$1,671 net benefit
- **Annual service charge (\$0.49/day):** ~\$179
- **Net annual benefit after service charge:** ~\$1,492

It is important to note that while this analysis applies the retail TOU rates for both imports and exports, actual customer compensation under Net Energy Metering 3.0 differs. Exported energy is credited at an avoided-cost rate tied to wholesale market conditions, which is typically lower than retail. Therefore, the export “savings” values presented here represent an upper bound, and real-world customer benefits would be expected to be lower once wholesale export rates are applied.

Overall, event trigger testing demonstrated that AHEMS 2 consistently followed its programmed TOU dispatch logic, creating measurable bill savings under retail rate assumptions but with a clear trade-off between economic optimization and resiliency.

In addition to economic outcomes, the team estimated reductions in GHG emissions by applying California’s average grid emissions factor of 80.55 grams of carbon dioxide equivalent per megajoule (gCO₂e/MJ), equivalent to 290 gCO₂e per kilowatt-hour (kWh) calculated in the Low Carbon Fuel Standard Annual Updates published by the California Air Resources Board (California Air

Resources Board 2024). Since rooftop solar is assumed to have zero operational emissions, avoided grid imports directly translate to avoided emissions.

From calculations daily energy use (energy sourced from the grid) is calculated to be 31.27, with daily energy savings (energy exported to grid) being 42.18 kWh. This would translate to 12.231 kilogram carbon dioxide equivalent (kgCO₂e) per day. Extrapolated over a full year of operation (365 days), AHEMS 2's TOU-driven behavior results in an estimated 4,464 kgCO₂e of avoided emissions annually.

Conclusion

The evaluation of advanced home energy management systems (AHEMS) to date has demonstrated that commercially available platforms with core solar and battery management functions, such as AHEMS 2 and 4, are capable of delivering high efficiencies and relatively stable performance across multiple energy pathways. However, while AHEMS 2 displayed both strong efficiency and predictable control behavior, AHEMS 4, despite its mature hardware, exhibited inconsistent and often counterproductive behavior during TOU operations. Both systems generally aligned with manufacturer claims, with only modest deviations that reflect expected real-world conditions.

By contrast, the systems incorporating vehicle-to-home (V2H) capabilities—AHEMS 1 and 3—were not functional for testing during this reporting period. In both cases, the provided units were early-stage prototypes or prereleases that encountered hardware or software limitations preventing throughput assessment. This outcome suggests that while DC-bussed architectures with integrated V2H represent a promising direction for future AHEMS development, these platforms remain in a formative stage and require additional engineering refinement before they can be considered production-ready.

Taken together, the results highlight a maturity gap within the current market: established, grid-tied and battery-centric systems are already performing reliably in terms of raw efficiency, but meaningful differences exist in developed control logic and end-user interaction. AHEMS 2 demonstrated coherent, tariff-driven behavior, whereas AHEMS 4 revealed deficiencies in TOU logic transparency, dataset availability, and core economic functionality, limiting its practical value for end users seeking bill optimization. As next-generation hardware becomes available, continued evaluation will be necessary to determine whether these more advanced architectures can deliver on their potential for broader residential energy flexibility.

In addition to technical performance, economic analysis of AHEMS 2 under the PG&E E-ELEC-NEM3.0 tariff demonstrated meaningful bill savings potential when operating under fixed TOU schedules. By strategically discharging during peak pricing periods and recharging during off-peak hours, the system achieved an estimated net annual benefit of approximately \$1,492 after accounting for daily service charges. While this represents an upper-bound scenario using retail export rates, actual customer benefits under NEM 3.0 would likely be more modest. Nevertheless, these results highlight that when TOU logic is implemented effectively, AHEMS platforms can provide not only operational efficiency but also tangible economic value to homeowners.

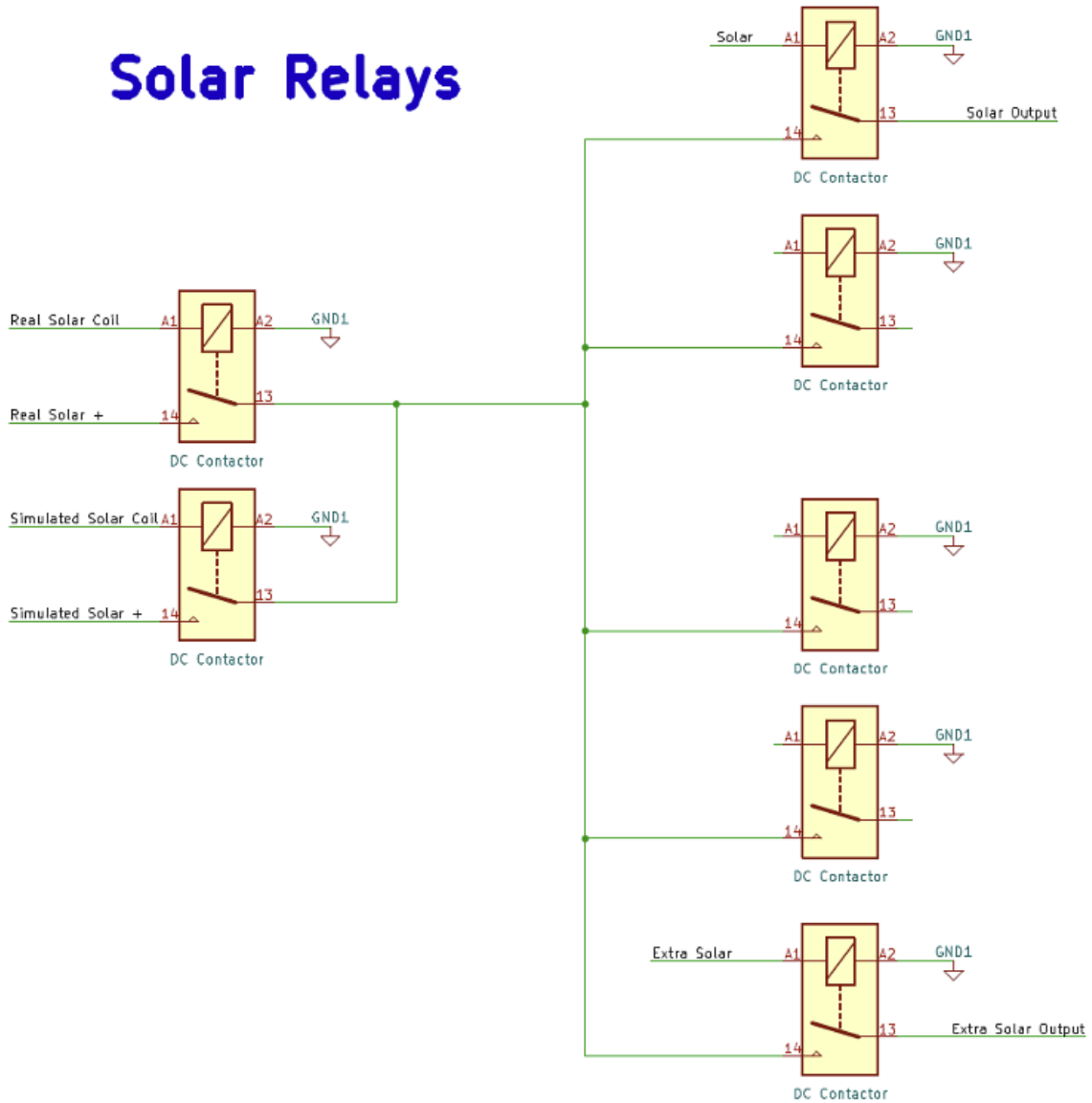
Finally, an emissions analysis using California's Low Carbon Fuel Standard average grid emission factor of 290 gCO₂e/kWh showed that avoided grid imports from AHEMS 2's operation could yield an estimated reduction of 4,464 kgCO₂e annually for a single-family home. These results demonstrate that while the system platform is optimized for bill savings, its behavior also translates into meaningful reductions in carbon emissions under current grid conditions.

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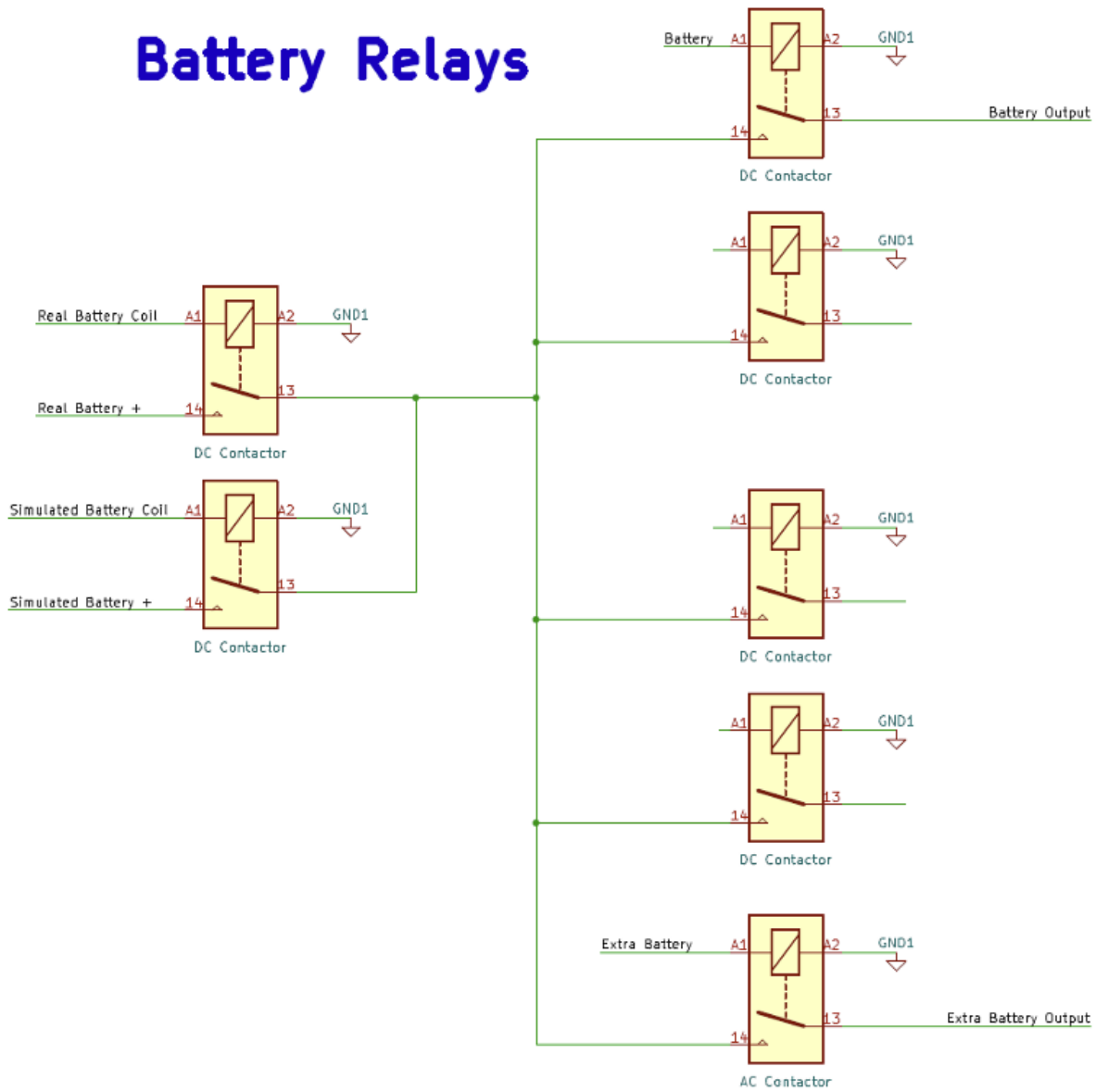
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Appendix A: Testbed Wiring

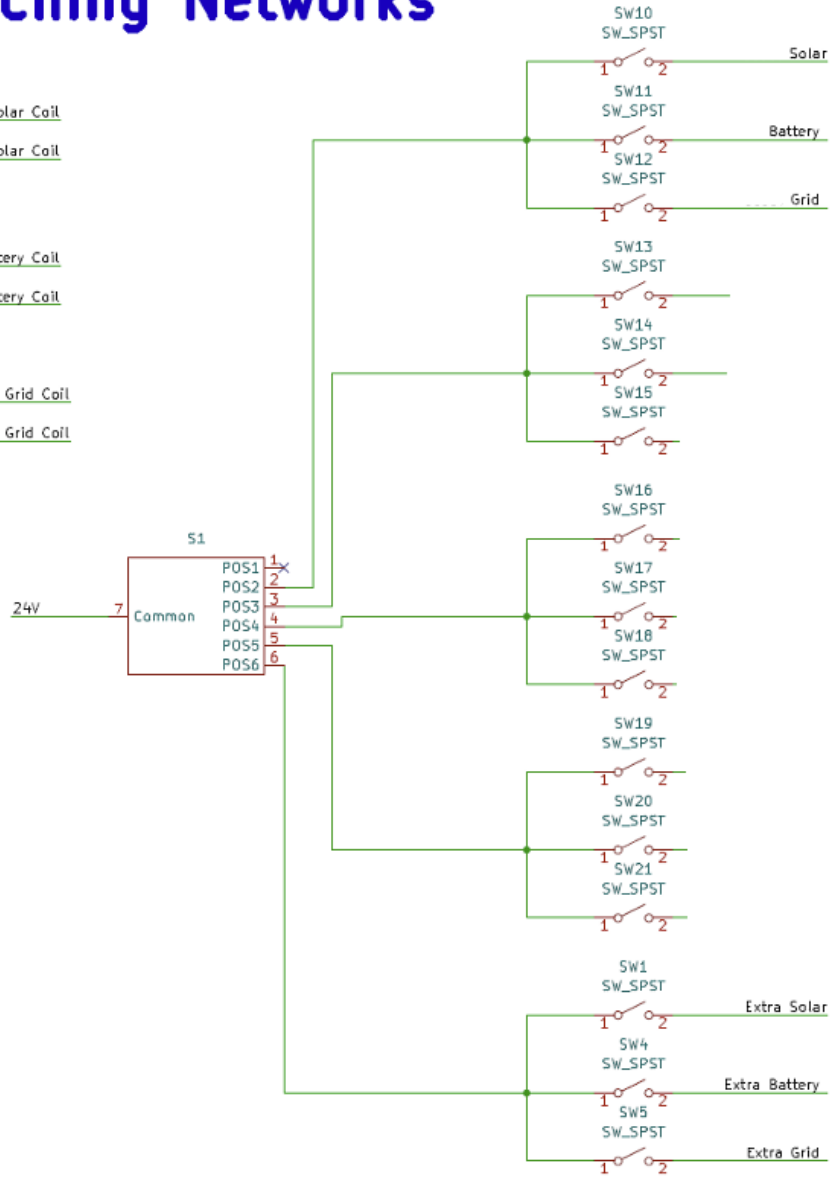
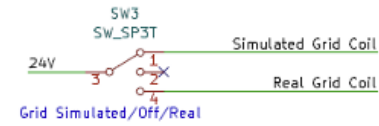
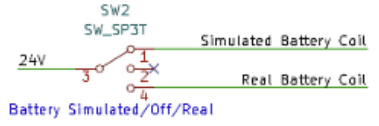
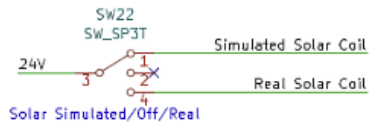
Solar Relays



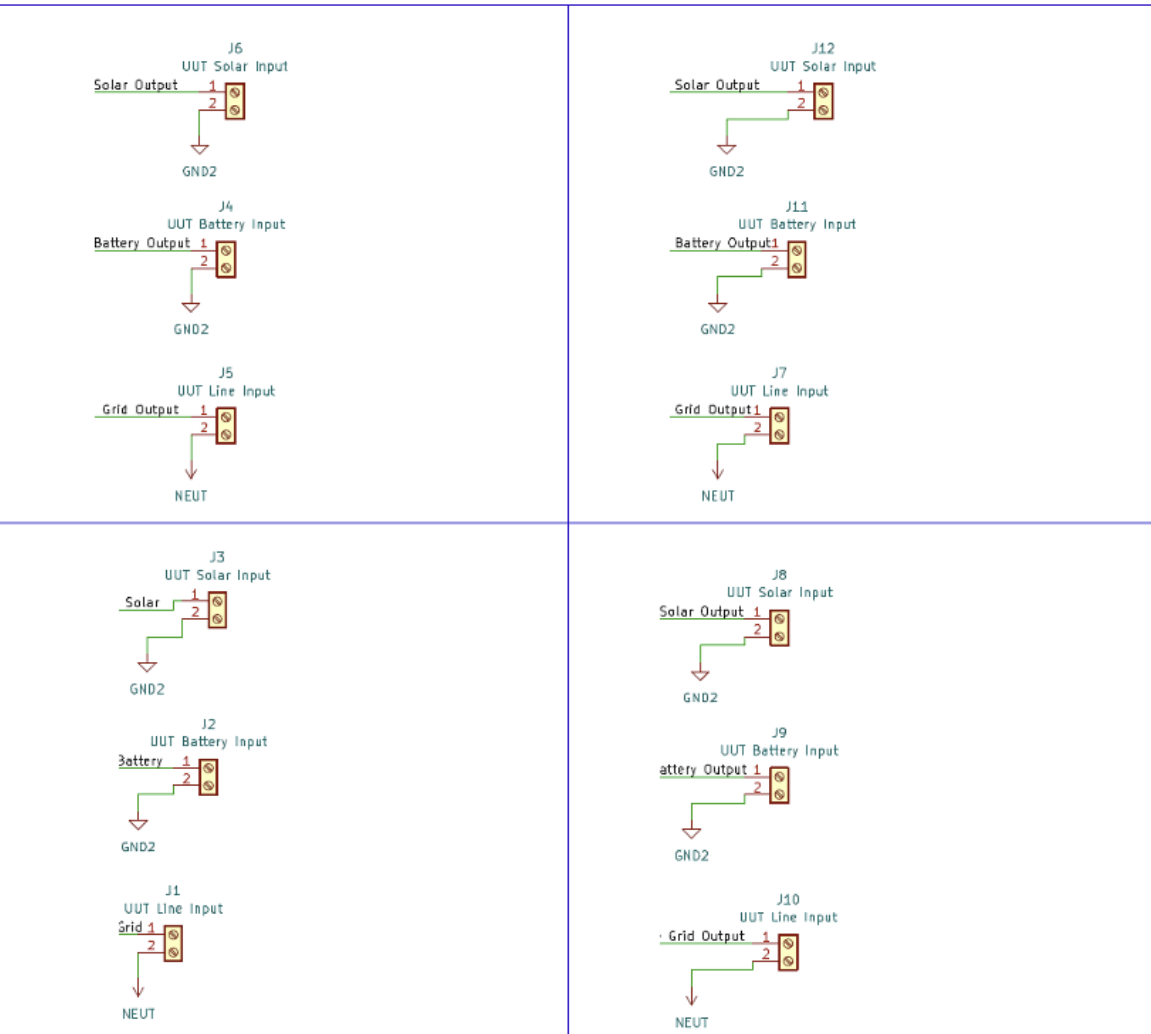
Battery Relays



Switching Networks



AHEMS UUTs



Grid Relays

