CALIFORNIA ENERGY COMMISSION

CALIFORNIA NATURAL RESOURCES AGENCY

ENERGY RESEARCH AND DEVELOPMENT DIVISION

FINAL PROJECT REPORT

Demand Based Renewable Hydrogen Power-to-Power Project

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PREFACE

The California Energy Commission's (CEC) Energy Research and Development Division supports energy research and development programs to spur innovation in energy efficiency, renewable energy and advanced clean generation, energy-related environmental protection, energy transmission, and distribution and transportation.

In 2012, the Electric Program Investment Charge (EPIC) was established by the California Public Utilities Commission to fund public investments in research to create and advance new energy solutions, foster regional innovation, and bring ideas from the lab to the marketplace. The EPIC program is funded by California utility customers under the auspices of the California Public Utilities Commission. The CEC and the state's three largest investor-owned utilities — Pacific Gas and Electric Company, San Diego Gas & Electric Company, and Southern California Edison Company — were selected to administer the EPIC funds and advance novel technologies, tools, and strategies that provide benefits to their electric ratepayers.

The CEC is committed to ensuring public participation in its research and development programs that promote greater reliability, lower costs, and increase safety for the California electric ratepayer and include:

- Providing societal benefits.
- Reducing greenhouse gas emission in the electricity sector at the lowest possible cost.
- Supporting California's loading order to meet energy needs, first with energy efficiency and demand response, next with renewable energy (distributed generation and utility scale), and finally with clean, conventional electricity supply.
- Supporting low-emission vehicles and transportation.
- Providing economic development.
- Using ratepayer funds efficiently.

Demand Based Renewable Hydrogen Power-to-Power Project is the final report for EPC-19-037 conducted by DasH2energy LLC. The information from this project contributes to the Energy Research and Development Division's EPIC Program.

For more information about the Energy Research and Development Division, please visit the CEC's research website (www.energy.ca.gov/research/) or contact the Energy Research and Development Division at ERDD@energy.ca.gov.

ABSTRACT

The Demand-Based Renewable Hydrogen Power-to-Power Project, led by DasH2energy and supported by the California Energy Commission under EPIC award EPC-19-037, aimed to develop, deploy, and evaluate a behind-the-meter hydrogen energy storage system integrating an alkaline electrolyzer, high-pressure hydrogen storage, and a proton exchange membrane fuel cell. The Power-to-Power system was installed and tested at the University of California, Irvine, using facility level electricity demand and renewable generation data provided by the Palmdale Water District.

The demonstration project validated the feasibility of using hydrogen produced via electrolysis as a long-duration energy storage solution capable of storing and then generating renewable electricity across monthly and seasonal timescales. Key technical milestones included real-world testing of system components under dynamic load conditions, development of electrochemical simulation models, and measurement and verification of performance metrics including round-trip efficiency, thermal management constraints, and long-term storage integrity.

While Power-to-Power systems have a relatively low round-trip efficiency, the project identified pathways for future improvement through system optimization including improved chiller sizing, partial-load operation strategies, and advanced controls. Business model analysis across multiple scenarios demonstrated economic viability under supportive policy frameworks and incentive programs.

The project contributed to California's statutory energy goals by demonstrating a non-lithium-ion, resilient, zero-emission long duration energy storage technology, and laid the groundwork for future technology development and deployment.

Keywords: dash clean energy, zero emission power, renewable energy, resilient power clean energy solutions, hydrogen power, green hydrogen, energy innovation

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Background

DasH2energy LLC, founded in 2017, is a California-based clean hydrogen development company focused on advancing fuel cell power generation solutions. As renewable electricity generation continues to grow — accounting for more than 41 percent of California's in-state electricity generation in 2023 — the need for long-duration energy storage has grown due to the intermittent nature of solar and wind. While short-duration storage technologies such as lithium-ion batteries are effective at addressing intra-day variability (for example, ramping and short-term intermittency), they are not well suited for managing multi-day or seasonal mismatches between renewable energy supply and electricity demand. Long-duration energy storage systems such as hydrogen-based are essential for bridging extended gaps in renewable generation caused by weather patterns, seasonal changes, or grid reliability events.

Converting excess renewables into hydrogen and then later converting it back to electricity via fuel cells, known as a power-to-power system, offers a potential pathway for hydrogen energy storage. However, barriers to commercialization of power-to-power systems remain significant. Electrolyzers and fuel cells involve high upfront capital costs as well as substantial balance-of-plant and thermal management requirements that increase operating costs. System-level round-trip efficiency typically ranges from 20 to 35 percent, substantially lower than battery-based storage, which reduces economic competitiveness under current energy pricing structures. In addition, hydrogen leakage across seals and fittings not only raises safety concerns but also undermines environmental benefits due to hydrogen's indirect climate warming effects. Finally, successful deployment requires advanced controls, thermal integration, and site-specific design, making system integration more complex than stand-alone battery or diesel generators. These challenges limit developer interest and slow market maturation despite the long-duration and zero-emission advantages hydrogen offers.

Project Purpose and Approach

To address these commercialization challenges, DasH2energy designed, developed, and demonstrated a power-to-power hydrogen system — integrating an alkaline electrolyzer, high-pressure hydrogen storage, and a stationary proton exchange membrane fuel cell targeted for customer-sited, behind-the-meter applications. The system was hosted and operated at the University of California, Irvine (UCI), providing a controlled research environment that allowed for detailed performance monitoring, data collection, and system optimization.

The project directly addressed key market barriers, including the following.

- System Integration Complexity: The project demonstrated successful end-to-end integration of electrolyzer, storage, and fuel cell subsystems using commercial hardware and controls, validating a replicable architecture for commercial and industrial customers.

- Low Round-Trip Efficiency: The team collected empirical data on stack and system-level efficiencies under multiple load and operating conditions, allowing real-world benchmarking of performance and loss factors.
- Capital and Operating Cost Uncertainty: The demonstration provided a detailed bill of materials and performance metrics to support techno-economic modeling and sensitivity analysis of cost drivers.
- Export and Interconnection Constraints: By using actual generation and load profiles from the Palmdale Water District the project simulated use cases in which hydrogen can capture otherwise curtailed renewable energy and return it later as dispatchable power, thus providing flexibility and grid relief without increasing site exports.

Data was collected over a 12-month operational period following system commissioning at UCI. The system was monitored using a combination of onboard instrumentation and external power metering and supervisory control and data acquisition logging. Real-time data was collected at one-minute intervals and stored for post-processing.

The primary objective of the demonstration was to evaluate the technical and economic performance of an integrated hydrogen system operating under realistic use cases for behind-the-meter customers. Specific goals included measuring round-trip efficiency under variable part-load conditions, identifying system losses and thermal requirements, validating the control strategy for electrolyzer-fuel cell coordination, and generating empirical data to support business case modeling for commercial and industrial sites with intermittent renewables and interconnection constraints.

Key Results and Conclusions

The integrated system was successfully demonstrated to validate key operational capabilities, including cold and hot starts, dynamic load-following, and sustained high-pressure hydrogen storage. Over a one-year testing period, the system maintained full containment with no measurable hydrogen leakage.

Electrolyzer stack efficiencies averaged 56 kilowatt-hours per kilogram of hydrogen produced, with an average system efficiency of 74 kilowatt-hours per kilogram of hydrogen. Fuel cell stack efficiencies averaged 42 percent with average system efficiency of around 18 percent. The combined electrolyzer-to-fuel cell round-trip efficiency was measured at 13 percent on a system level, with observed optimization pathways targeting up to 32 percent improvement, including through rightsizing chiller systems, operating at partial load, and enhancing thermal integration across subsystems.

Using the performance data collected at UCI, the project team developed and validated electrochemical and thermodynamic models to simulate hydrogen system performance under variable renewable electricity production and load data from the Palmdale Water District. These simulations enabled characterization of stack behavior, thermal requirements, degradation effects, and round-trip efficiency across different distributed energy resource configurations, including solar, wind, and hybrid scenarios.

The project also evaluated business model viability under California's evolving policy frameworks. Scenarios leveraging net energy metering 3.0, the Avoided Cost Calculator and Self-Generation Incentive Program were modeled to assess revenue potential and value stacking opportunities. The project team proposed policy and program reforms that could enable greater commercial viability for hydrogen systems by recognizing their long-duration storage, backup power, and resiliency benefits.

Knowledge Transfer and Next Steps

Knowledge transfer was a central pillar of the project, aimed at building confidence in hydrogen as a viable, scalable long-duration energy storage solution. Over the course of the demonstration, the project team hosted 24 technical site tours with attendees including representatives from Community Choice Aggregators (Lancaster Energy, California Community Power), investor-owned and municipal utilities, the California Energy Commission, the U.S. Department of Energy, regional air quality management districts, independent power producers, and private equity investment firms, including Tallgrass Energy. Feedback from these tours consistently highlighted the value of seeing an integrated electrolyzer, storage, and fuel cell system in real-world operation.

Project findings were shared through seven industry presentations, including at the California Community Choice Aggregators Annual Conference (2023), California Hydrogen Leadership Summit (2023), Hydrogen Americas Summit (2023), Advanced Clean Transportation Expo, Energy Storage North America, and Hydrogen and Fuel Cell Seminar (2025).

The project's outreach campaign also included regular updates through LinkedIn, generating more than 34,000 impressions and several hundred engagements. These communications significantly increased visibility with potential partners and led to inquiries from utilities, clean tech investors, and other applicants to the Department of Energy's Hydrogen Hub program.

These outreach and demonstration efforts directly helped DasH2energy secure its role in the Alliance for Renewable Clean Hydrogen Energy Systems Hydrogen Hub, where it was awarded funding for a 20-megawatt resource adequacy project in partnership with Lancaster Choice Energy. Additionally, connections formed during the UCI demonstration enabled collaborations with hydrogen compression and distribution vendors, helping shape joint development agreements for future projects.

Looking forward, DasH2energy is advancing several commercial initiatives in addition to Lancaster including the following.

- Design of modular behind-the-meter hydrogen systems for school districts and water agencies, with the first 2,500 kilowatts planned for deployment in 2026
- Design of distributed front of the meter fuel cell systems, with 9 megawatts being deployed in 2027
- Collaboration with Community Choice Aggregators partners to develop resiliency-focused fuel cell projects
- Feasibility assessments for green hydrogen microgrids

These next steps aim to transition hydrogen energy storage from pilot demonstrations to commercial deployments by replicating lessons learned from this project and scaling integrated system architectures in real-world customer applications.

Benefits to California Ratepayers

This project provides a replicable model for the ways hydrogen-based energy storage can directly benefit California ratepayers by reducing costs, enhancing reliability, and supporting cleaner energy consumption. By enabling customers to store excess renewable energy and dispatch it during peak demand periods, hydrogen systems could help balance variable supply and demand and help meet system peaks with otherwise curtailed renewable electricity.

Hydrogen also provides a zero-emission backup power alternative to diesel generators, improving air quality and public health in disadvantaged communities that are often disproportionately affected by pollution and outages. For municipal facilities such as water districts or emergency shelters, hydrogen energy storage increases local resiliency, reducing dependence on centralized grid infrastructure and the associated risk of public safety power shutoffs.

In the longer term, hydrogen offers a pathway to reduce interconnection and distribution system upgrade costs by allowing energy to be stored and used on site rather than exported to congested circuits. As hydrogen storage technologies scale and become more cost effective, they will offer ratepayers access to a broader portfolio of clean, flexible, and dispatchable energy options — helping to stabilize long-term utility rates while supporting system reliability.

CHAPTER 1: Introduction

Problem Statement

California's energy system is rapidly decarbonizing, with renewable electricity sources — primarily solar and wind — accounting for more than 41 percent of in-state generation in 2023. However, the variability and intermittency of these resources are straining the existing electricity grid and highlighting the need for long-duration energy storage (LDES) solutions that can store renewable electricity for multiple days or even seasons. LDES is essential for ensuring reliability during prolonged periods of low renewable output, supporting grid resilience, and enabling higher renewable penetration.

Hydrogen energy storage offers a promising pathway for meeting these needs. Hydrogen is scalable, can store energy seasonally, and serves multiple functions including long-duration discharge, backup power, and grid services. However, several barriers have hindered its commercialization, particularly in behind-the-meter (BTM) or distributed applications. These barriers include high capital and operating costs for electrolyzers, compressors, and fuel cells; low round-trip efficiency (RTE) compared to lithium-ion batteries; hydrogen leakage risks and associated environmental and safety concerns; lack of integrated developers or business models that offer turnkey solutions; and complex system integration and controls requirements to operate efficiently at small scale.

This demonstration project was designed to address these barriers and generate real-world performance data to inform the technical, economic, and operational viability of hydrogen as an LDES solution. By integrating an electrolyzer, hydrogen storage, and a fuel cell at a test site and applying site load and renewable profiles from a real customer, the project evaluated use cases where large distributed energy resource (DER) installations are otherwise blocked by costly interconnection upgrades. This subset of the market, including water agencies, school districts, and industrial customers, presents a near-term opportunity for hydrogen systems that can store excess on-site renewables without exporting to the grid.

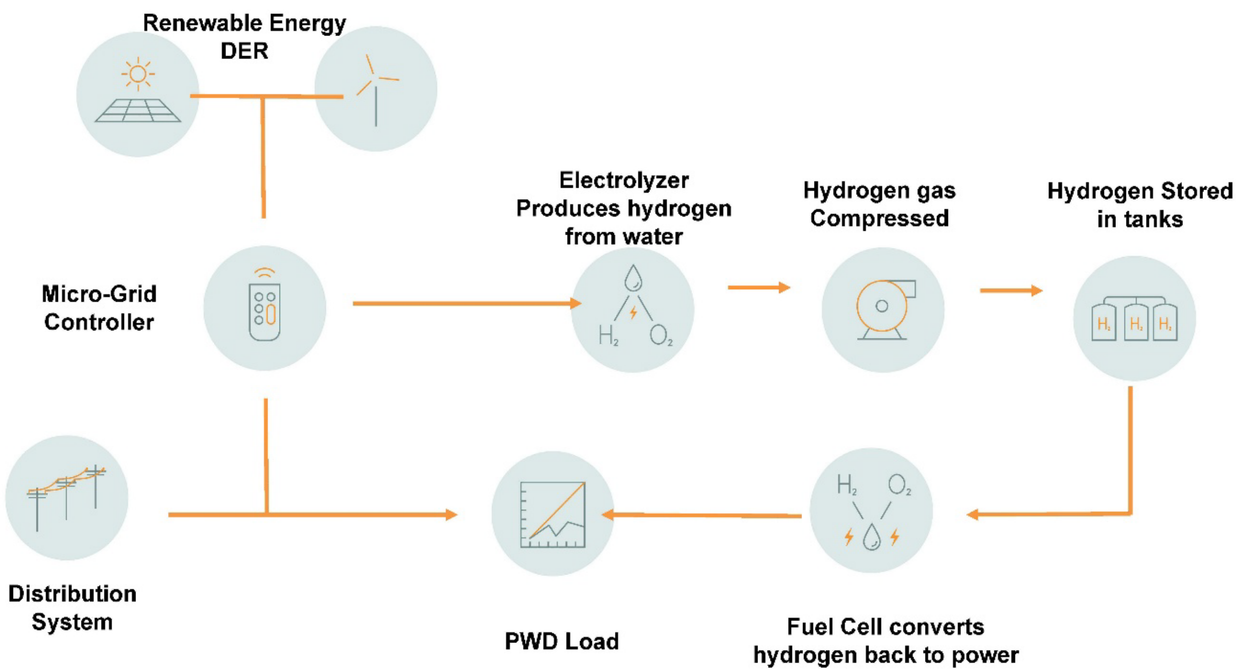
Ultimately, this project aimed to de-risk hydrogen technologies for DER applications and provide a replicable model for the ways hydrogen can support California's reliability, resiliency, and decarbonization goals — while also identifying specific market conditions where hydrogen can compete with other storage options.

CHAPTER 2: Project Approach

The power-to-power (P2P) project was designed to demonstrate a complete hydrogen-based energy storage system that could serve as a long-duration, BTM solution for commercial and industrial customers. The system operates by consuming renewable electricity to produce hydrogen via electrolysis, storing the hydrogen in high-pressure composite tanks, and later converting it back to electricity through a stationary proton exchange membrane fuel cell (PEMFC) for use during peak demand or outage events. Figure 1 provides a high-level schematic of the system, including key components such as the electrolyzer, hydrogen storage, fuel cell, grid connection, and representative site loads and DERs.

While the physical demonstration system was installed, commissioned, and operated at the University of California, Irvine (UCI), the project design was informed by actual electricity demand and renewable generation data collected from Palmdale Water District (PWD). This included hourly load profiles and modeled solar and wind production data from PWD's site, which served as the operational baseline for system design and performance evaluation.

Figure 1: Power-to-Power Configuration



Source: DasH2energy

The demonstration tested the system's ability to handle variable renewable inputs, follow dynamic load conditions, perform hot and cold starts, and respond to backup power events. Performance data was collected and used to simulate how a fully deployed hydrogen system would behave in various conditions, with findings used to assess broader technical and economic feasibility for similar customer types.

Project Team

DasH2enegry

DasH2energy (D2E) is a hydrogen fuel cell project development company and is the lead principal investigator for the project. D2E led the grant management, project management including procurement, engineering, construction, and operations. Finally, D2E was responsible for the business modeling and business case analysis for the project.

Palmdale Water District

The PWD, which supplies clean drinking water to the city of Palmdale, partnered with D2E to provide site-specific energy demand, renewable generation, and economic data. The project team used this information to evaluate potential alternatives for replacing PWD's existing wind turbine.

University of California, Irvine

UCI was responsible for hosting the demonstration site, including the installation of all equipment, and conducting experimental operations, data collection, and the development of analytical tools to evaluate the cost and performance of the P2P system.

Teledyne Energy Systems, Inc.

Teledyne Energy Systems, Inc. (TESI) was contracted to provide the issued-for-construction design package for the containerized electrolyzer and compressor. Additionally, TESI constructed the containerized system that housed the electrolyzer and compressor.

Toyota Motor Company

Toyota was the manufacturer of hydrogen fuel cell technology and donated a redesigned fuel cell from its first-generation Toyota Mirai vehicle to operate as a stationary generator. Toyota also provided support on start-up and commissioning of the fuel cell.

Jenson-Hughes

Jensen Hughes is an independent third-party consultant that provided the National Fire Protection Association (NFPA) code analysis for the hydrogen generation and storage system.

Project Tasks

Baseline Data Gathering at PWD

PWD is currently enrolled in Southern California Edison's (SCE) time of use (TOU)-GS-3 rate schedule, which applies to large commercial customers. This rate includes significant demand charges and time-varying energy prices. Key rate components include summer On-Peak demand charges of $13.53 per kilowatt (kW) and energy and generation charges based on season and time as outlined in Table 1.

Table 1: Palmdale Water District Time-of-Use Energy Charges

	Energy	Generation	Total
Summer			
On-Peak	$0.33	$0.32	$0.65
Off-Peak	$0.19	$0.10	$0.29
Super Off-Peak	$0.10	$0.07	$0.17
Winter			
On-Peak	$0.06	$0.15	$0.21
Off-Peak	$0.04	$0.08	$0.12
Super Off-Peak	$0.05	$0.04	$0.09

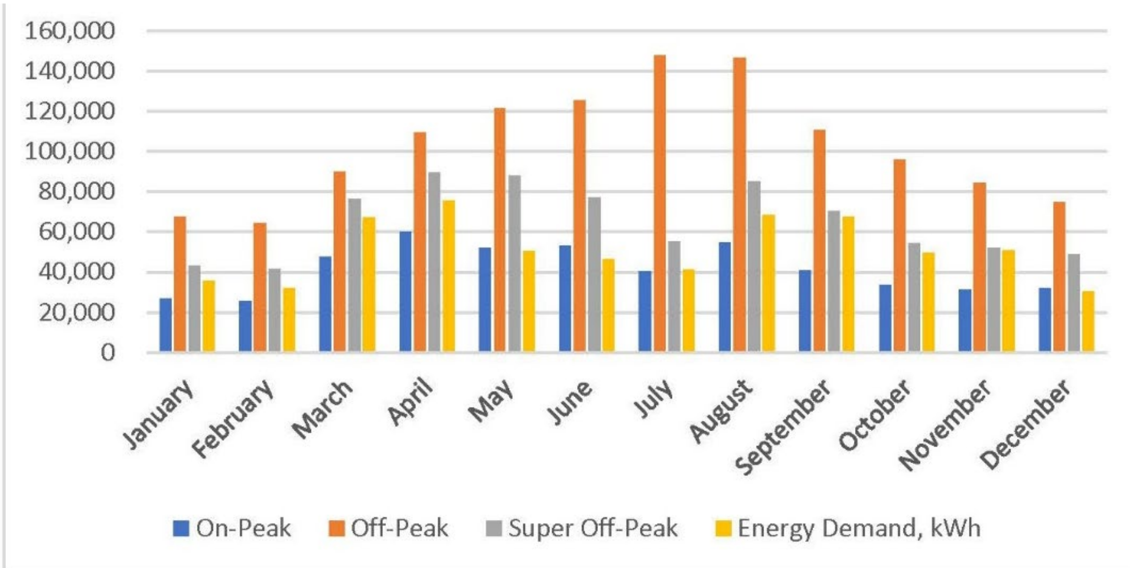
Source: Southern California Edison

In 2020, PWD consumed approximately 2,519,300 kilowatt-hours (kWh) of electricity while operating their current DER, a Neg-Micon 950 kW wind turbine generator (WTG), as shown in Figure 2. The WTG supplied about 48 percent of this total (1,209,265 kWh), with 16 percent (403,088 kWh) of total usage exported to the grid under net energy metering (NEM) 1.0. Under this earlier policy structure, PWD received near-retail compensation for exported energy, improving project economics significantly. The remainder energy came from the grid, as shown in the monthly usage data in Figure 3.

Figure 2: Palmdale Water District's Existing Wind Turbine Generator

Source: DasH2energy

Figure 3: Palmdale Water District's Energy Usage per Month



Source: DasH2energy

Conceptual System Design

In evaluating hydrogen system components for the UCI demonstration site, the project team considered all major electrolyzer types including proton exchange membrane, alkaline, and anion exchange membrane (AEM) systems. UCI had recently completed a separate research grant evaluating a PEM (protein exchange membrane)-based electrolyzer, and the project team sought to validate a different electrolysis pathway for broader comparative value. While AEM electrolyzers are promising in lab-scale research, no commercially available AEM systems with adequate vendor support were found at the time of procurement, eliminating that technology from consideration.

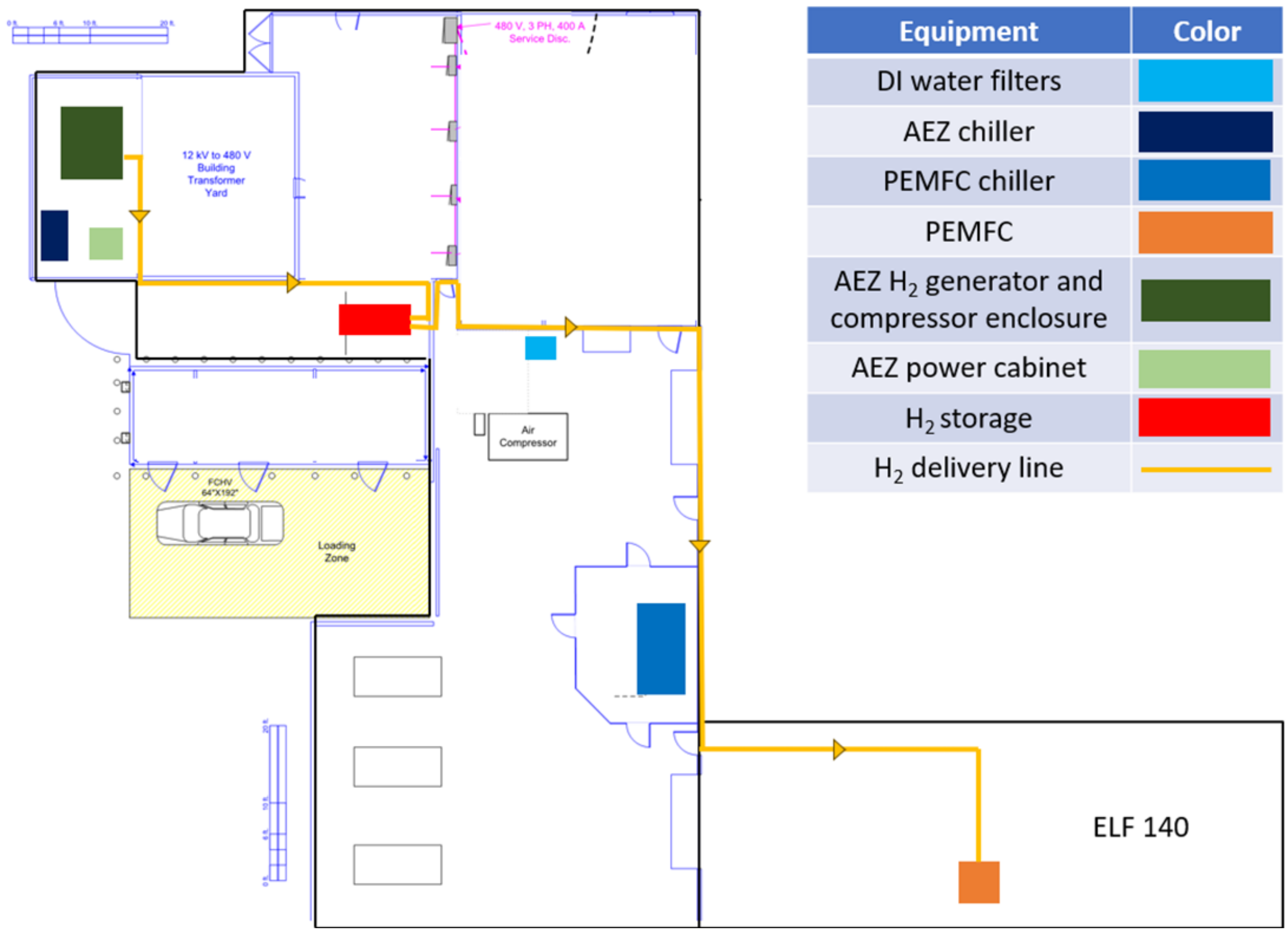
This left alkaline electrolysis as the most viable path forward. After a limited market scan, the project team selected TESI, as the only United States-based manufacturer that met the project's requirements and timelines. TESI also recommended a compatible diaphragm compressor, ensuring thermal and operational integration across the hydrogen production system. These real-world procurement constraints, in combination with the research goals, shaped the final system architecture deployed at UCI.

To evaluate various DER configurations for the site-specific P2P system, the project leveraged data collected during the initial phase at PWD including 15-minute interval energy usage, historical wind turbine performance, and utility rate structures. Using this data, the team developed models to simulate the technical performance, energy production, and cost implications of multiple DER scenarios.

Preliminary System Design

The preliminary design phase for the demonstration site involved laying out the selected equipment and drafting the initial routing for hydrogen pipelines, deionized water (DI) supply lines, and electrical interconnections. The project team also developed a detailed specification sheet that outlined the chosen equipment and their proposed locations, which served as the foundation for the final design. Figure 4 illustrates the preliminary site layout at UCI, including the Engineering Laboratory Facility 140, which housed the PEMFC.

Figure 4: Preliminary Demonstration Site Layout at UCI



Source: University of California, Irvine

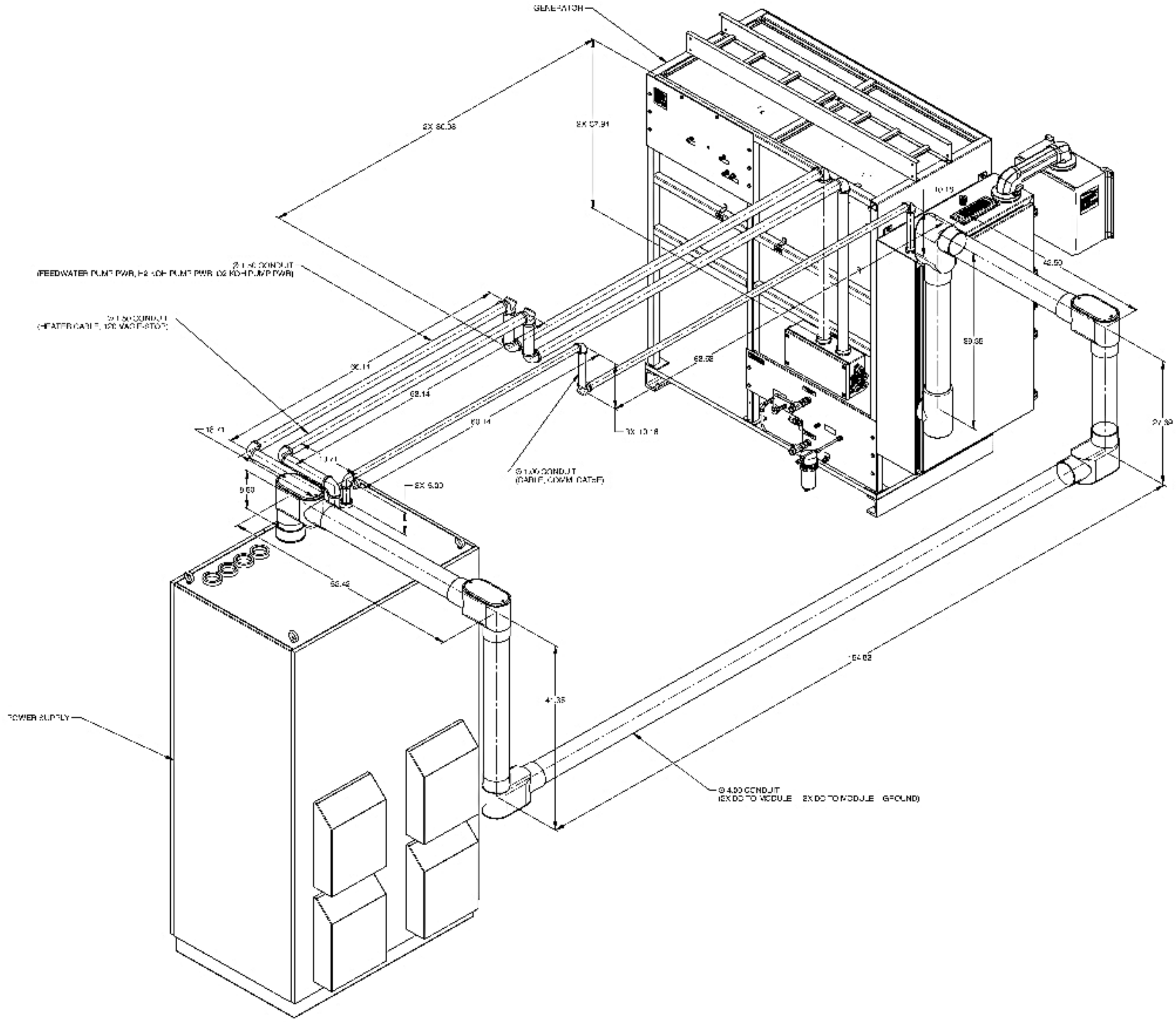
Detailed Design Phase

Detailed design packages were developed for installation of equipment and construction of the project, for example as shown in Figure 5, which depicts the piping and instrumentation drawings. TESI completed the issued-for-construction package, which included the following similarly detailed drawings.

- General arrangement drawings for the electrolyzer, compressor, and storage
- Piping and instrumentation diagrams for the electrolyzer, compressor, and storage
- Single line diagram for the power supply, electrolyzer, and compressor
- Installation drawings for the power supply, electrolyzer, compressor and storage
- Field wiring diagram drawings for the power supply, electrolyzer, and compressor

- Bill of materials for the electrolyzer, compressor and storage
- External piping and tubing installation drawings

Figure 5: External Piping and Tubing Installation Drawings



Source: Teledyne Energy Systems, Inc.

Safety Plan

To ensure compliance with applicable safety standards, Jensen Hughes conducted a comprehensive site assessment and issued a final report detailing findings and recommended actions. Based on its evaluation, the project implemented the following corrective measures to address and align with the requirements of NFPA 2 and NFPA 70.

- Capping or Removal of Unused Lines: All unused gas and electrical lines were either capped or completely removed. The project successfully removed abandoned pipelines and conduits to eliminate potential hazards.

- Hydrogen Vent Line Elevation: Hydrogen vent lines were extended to a minimum of 5 feet above rooftop level. Instrumentation and isolation valves were installed on both the inlet and outlet of the hydrogen delivery lines connected to the storage units. These instruments support remote operation and monitoring of both the filling and discharging processes, enhancing operational safety.
- Rooftop Ventilation Clearance: To meet the requirement of maintaining at least 18 inches of vertical clearance between the base of rooftop structures and surrounding walls for proper hydrogen ventilation, sections of the rooftop structure were removed.
- Fire-Rated Barrier for Utilities: Active gas and electrical lines were required to be located behind a two-hour fire-rated concrete wall. The project complied by relocating natural gas, mixed gas pipelines, and electrical service lines to the opposite side of the rated barrier and reinstalling them accordingly.
- Administrative Controls and Safety Documentation: Proper administrative controls were established, including the development of a safety binder containing standard operating procedures, emergency contact information, and relevant safety protocols. Appropriate hazard signage was also installed at the site, as shown in Figure 6.

Figure 6: Posted Safety Signage

Source: DasH2energy

In addition to these physical and procedural safety upgrades, several lessons learned and best practices emerged during the design and commissioning process that may support future hydrogen deployments, including the following.

- Engage local fire marshals: The project team reduced delays by initiating discussions before permitting, providing educational materials, and walking through the hydrogen use case with local officials.

- Pre-integrated gas detection and shutdown systems are critical: Using pre-tested gas sensors and integrated automatic shutoff valves simplified commissioning and improved stakeholder confidence.
- Ventilation design matters: Passive rooftop ventilation, combined with hydrogen's natural buoyancy, allowed for a simpler design and avoided costly hazardous zoning requirements.

Overall, the safety framework developed for this project demonstrated that hydrogen systems can be safely and affordably deployed at commercial and institutional sites when early planning, code compliance, and collaborative engagement are prioritized.

Procurement, Construction, and Commissioning

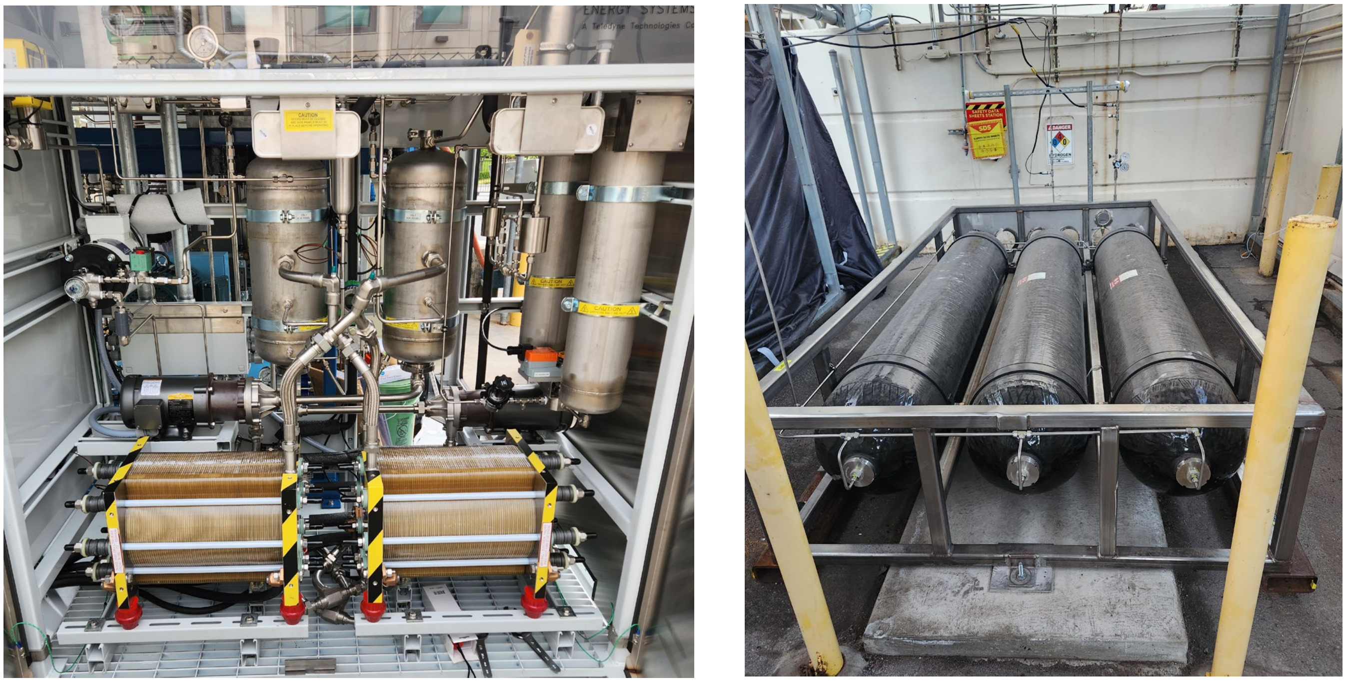
Figure 7 shows the existing pad for the electrolyzer and compressor, which already included existing electrical and DI water hookups (left), and the installation of the electrolyzer (right). These pre-established infrastructure elements supported the integration of the electrolyzer, compressor, and storage units into the demonstration system.

Figure 7: Pre-Existing Pad and Installation of Containerized Alkaline Electrolyzer

Source: University of California, Irvine and DaH2energy

The procurement phase of the project spanned approximately 12 months and included acquisition of key components, shown in Figure 8, such as a 24 kilogram-per-day alkaline electrolyzer (AEZ), left, and hydrogen storage, right, with an 18-kilogram (kg) capacity at 5,000 pounds per square inch. All equipment was delivered and installed in April 2023. Commissioning activities were carried out over the following 12 months, with formal commissioning completed in January 2024. The electrolyzer and hydrogen storage system were connected to an existing 50-kW fuel cell in the UCI laboratory repurposed for stationary applications from Toyota Motor Company (Figure 9).

Figure 8: Alkaline Electrolyzer and High-Pressure Hydrogen Storage



Source: DasH2energy

Figure 9: Proton Exchange Membrane Fuel Cell

Source: University of California, Irvine

Measurement and Verification

The project's measurement and verification (M&V) plan was designed to generate high-resolution performance data from the integrated hydrogen system to validate technical operation, quantify RTE, and support techno-economic modeling for commercial replication. The M&V plan included the following activities.

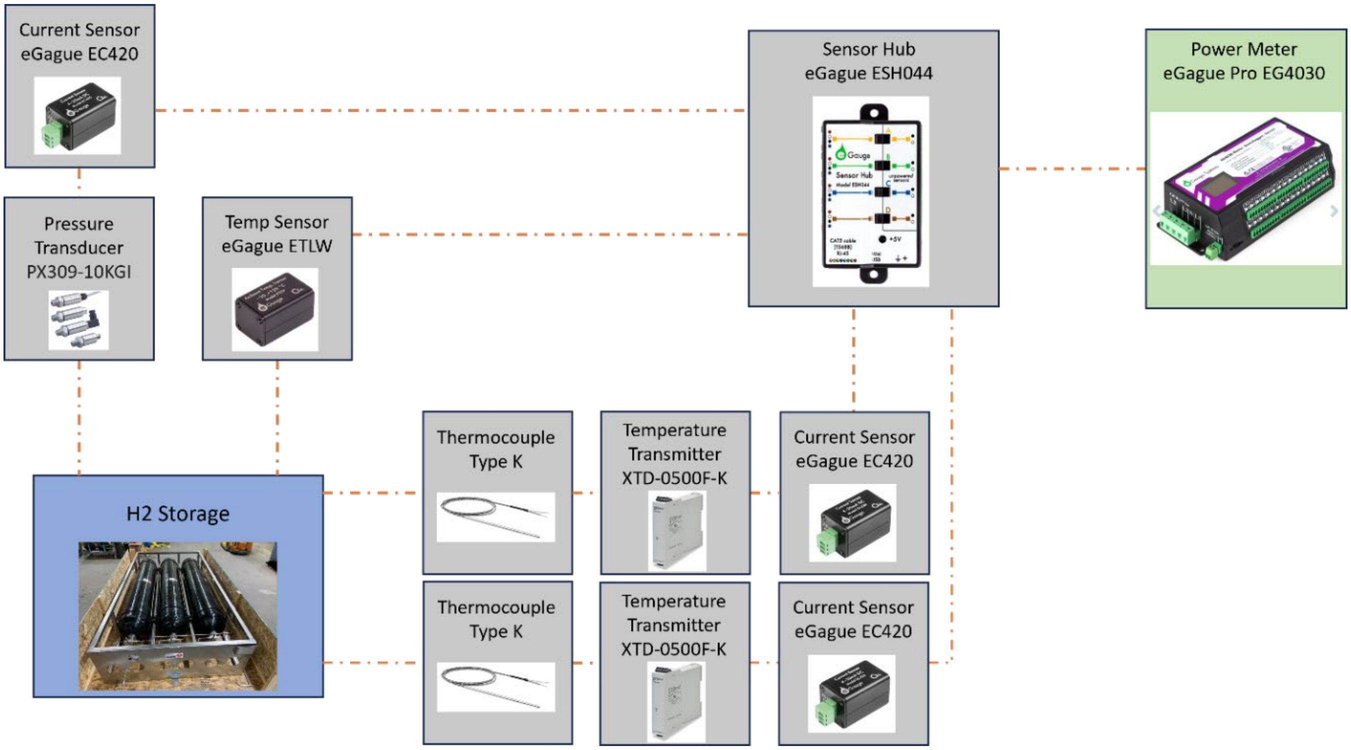
- Installation of dedicated metering equipment to monitor power flows into and out of the electrolyzer and fuel cell, as well as auxiliary loads such as chillers and compressors
- Hydrogen production and consumption measurement using calibrated flow meters, pressure transducers, and storage tank level sensors
- Thermal monitoring of stack inlet/outlet temperatures and chiller performance to quantify system losses and cooling requirements
- Benchmark performance testing under controlled and variable load conditions to evaluate stack efficiency, partial load operation, start-up/shutdown behavior, and load-following response time
- Development and validation of electrochemical and system-level models, using the empirical data to simulate system performance under different load profiles, DER configurations, and economic scenarios.

This comprehensive data set was essential for 1) validating the RTE of the integrated system under real-world conditions, 2) identifying optimization pathways including chiller right sizing, thermal recovery, and load management strategies, and 3) informing the business case for hydrogen storage, including cost per kWh of delivered electricity, demand charge reduction, and resiliency value. By aligning technical performance data with economic modeling, the M&V process helped bridge the gap between demonstration and commercialization.

Installation of Metering System

While each major component was equipped with its own programmable logic controller (PLC) for routine monitoring and control, the internal measurements alone were insufficient to evaluate the performance of the system as an integrated P2P system. To address this, an external data acquisition system (DAQ) was installed across the P2P site to supplement the PLC data and provide a more comprehensive view of system-level performance. Figure 10 illustrates the DAQ configuration implemented by the project team.

Figure 10: Data Acquisition Schematic for Hydrogen Storage Instrumentation



Source: University of California, Irvine

Technology Benchmark Plan

The metering system enabled the project to conduct a detailed performance evaluation of each individual component. Initial operation included steady-state characterization tests across a range of hydrogen production rates to assess system behavior at various operating points. The project team collected a range of data and performance metrics that allowed evaluation of system performance, characterization of operational limits, assessment of durability and degradation, and validation of hydrogen (H2) storage safety and compliance with no leakage. Specific data and performance metrics collected for each of these objectives, along with details on measurements and calculations, are described below.

Evaluate Performance Metrics

- Hydrogen production rate (kilograms per hour): Measured via mass flow meters and pressure sensors on the hydrogen outlet. This metric quantifies electrolyzer throughput and informs system sizing.
- Electrical efficiency at the stack and system level: Stack efficiency was calculated as the ratio of hydrogen's lower heating value to electrical input. System-level efficiency included balance-of-plant (BoP) loads such as chillers and compressors. This indicated real-world energy conversion effectiveness.
- Specific energy consumption (kilowatt-hours per kilogram [kWh/kg]): Total electricity used divided by hydrogen produced. This is a key metric for economic competitiveness, with typical values ranging from 50 to 70 kWh/kg depending on load and temperature.

- Stack voltage efficiency and current density: Voltage efficiency compared actual cell voltage to the theoretical minimum. Current density was measured using internal stack diagnostics. These values affect stack performance, efficiency, and degradation rates.
- Faradaic efficiency: The percentage of current contributing to hydrogen production, calculated by comparing theoretical hydrogen output to actual measured flow. This reflects the system's electrochemical efficiency and is sensitive to gas crossover or parasitic reactions.

Characterize Operational Limits

- Load-following capability: The system was evaluated for its ability to adjust hydrogen production and fuel cell output in response to fluctuating loads. This was tested by simulating solar/wind intermittency. Rapid response (sub-minute) was confirmed for the PEMFC.
- Startup/shutdown times: Cold and hot start durations were recorded. The PEMFC demonstrated sub-10-minute hot restarts, while the electrolyzer start-up was dependent on thermal readiness (approximately 30 to 60 minutes).
- Partial-load performance: Efficiency curves were developed across different partial-load conditions. Both the electrolyzer and fuel cell operated with improved efficiency at partial loads, revealing an opportunity for smart dispatch.
- Response to fluctuating renewable input: Renewable generation profiles from PWD were used to simulate variable input. The system showed stable operation under rapid fluctuations and successfully curtailed production to maintain hydrogen pressure limits.

Assess Durability and Degradation

- Performance over extended hours: System operation spanned a 12-month period. Electrochemical performance metrics were tracked over time to establish baseline degradation rates.
- Impact of contaminants, temperature, or cycling: Variability in ambient conditions and cycling frequency was logged alongside performance. No significant performance loss was observed, though operating temperature swings did impact chiller performance and stack voltage slightly.

Validate Safety and Compliance

- Leak rates: Hydrogen leakage was assessed using a combination of thermocouples, pressure transducers, and long-term pressure monitoring of the high-pressure composite storage tanks. After the tanks were filled, they were left idle and observed over a 12-month period. Throughout that time, no measurable drop in hydrogen pressure was recorded, confirming the integrity of the storage vessels and associated piping. This long-duration, passive monitoring approach provided strong evidence that the system met or exceeded NFPA 2 leak containment standards and posed no significant safety risks during standby operation.

Electrochemical Simulation Model

The electrochemical simulation model was developed to evaluate and predict the performance of the hydrogen production and conversion system — specifically the AEZ and PEMFC. The model enabled the project team to do the following.

- Interpret and extrapolate performance data collected from the UCI demonstration.
- Simulate how the system would perform following PWD load and renewable generation profiles.
- Evaluate trade-offs in efficiency, system sizing, and operating strategies.
- Support business case modeling by estimating hydrogen production and RTE across different scenarios.

The model was built on electrochemical and thermodynamic equations, including the following.

- Nernst Equation: Determines the theoretical reversible voltage of the cell based on temperature, pressure, and reactant concentrations.
- Ohmic Losses: Represent resistance from ion transport through the membrane/electrolyte and electrical losses in the electrodes and external circuitry.
- Activation Overpotential: Modeled using the Tafel or Butler–Volmer equations, this quantifies the voltage losses due to the kinetics of the electrochemical reactions (for example, oxygen evolution or hydrogen oxidation).
- Concentration Overpotential: Captures voltage losses due to reactant/product mass transport limitations, particularly at high current densities.

Model inputs included operating temperature, cell pressure, current density, membrane/electrolyte properties, gas crossover rate, and Faradaic efficiency. These parameters are significant because they directly impact system energy consumption, hydrogen yield, degradation potential, and control strategies — all of which are critical to sizing and operating hydrogen systems effectively in commercial settings.

Ultimately, the simulation model served as a bridge between lab-scale demonstration and real-world deployment, allowing the team to quantify performance, validate system design choices, and inform scale-up decisions.

Techno-Economic Analysis and Business Model Design

The project leveraged the simulation model to quantify hydrogen production, storage requirements, and power generation, forming the basis for evaluating capital and operational costs, system lifespan, energy savings, payback periods, and greenhouse gas (GHG) reductions. The simulation and economic evaluation had to account for several constraints specific to the PWD site including 1) NEM limitations at a maximum of 950 kW, above which would trigger costly grid upgrades, and 2) system sizing restrictions that cap generation system size at 150 percent of the customer's historical annual load. Within these constraints, the project evaluated several different scenarios of DERs and various hybrid configurations as described below.

Scenario 1: Vestas Wind Turbine Generator Only

This scenario modeled a two-megawatt wind turbine generator (WTG) whose entire energy output is used to produce hydrogen via the electrolyzer. The hydrogen is later converted back to electricity using the PEMFC. The system is fully self-contained, with no grid export.

Scenario 2: Vestas Wind Turbine Generator with a Microgrid Controller

A microgrid controller manages the distribution of wind-generated electricity, prioritizing direct use to meet PWD's demand. Excess energy is converted to hydrogen, which can be stored for peak demand and dispatchability.

Scenario 3: One Megawatt Wind Turbine Generator with One Megawatt Solar Microgrid

In this case, the WTG and solar microgrid prioritize direct electricity consumption to meet PWD energy demand. Excess energy is converted to hydrogen, which can be stored for peak demand and dispatchability.

Scenario 4: Proton Exchange Membrane Fuel Cell with Avoided Cost Calculator Model

The Avoided Cost Calculator (ACC) model is a tool developed by the California Public Utilities Commission (CPUC) to estimate the value of electricity generation from DERs by calculating the "avoided cost" to the utility — essentially the cost the utility avoids by not having to generate or purchase additional power from centralized sources.[1] The ACC generates hourly pricing values per megawatt hour for every day of the year and varies by utility, location, and time.

In this scenario, the electrolyzer operates during low-value periods — defined by the lowest hourly ACC pricing windows, typically midday when solar overgeneration depresses system value. Hydrogen is stored for extended durations and later used by the fuel cell to provide on-site peak power during high demand or grid stress periods. This extended discharge duration and time-shifted energy use qualifies the system as long-duration energy storage (LDES), in contrast to short-duration battery cycles that only shift energy within a single day.

Scenario 5: Proton Exchange Membrane Fuel Cell with Delivered Hydrogen

Under this scenario, the project evaluated a business model in which a centralized electrolyzer produced hydrogen that could be delivered for less than six dollars per kilogram.

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[1] California Public Utilities Commission (CPUC). 2024. "DER Cost Effectiveness." Available at https://www.cpuc.ca.gov/industries-and-topics/electrical-energy/demand-side-management/energy-efficiency/der-cost-effectiveness.

Modeling Methodology

The project team used a custom techno-economic model to simulate hourly dispatch across a typical meteorological year. The data inputs included generation, demand, and cost data from PWD, simulated solar and wind generation using the System Advisor Model developed by the National Renewable Energy Laboratory, fuel cell and electrolyzer production based on part-load curves, and microgrid controller to manage power flows for each scenario.

The outputs of the model included hydrogen production/consumption (kg per year), energy delivered to PWD (kWh/year), financial savings compared to a grid-only baseline, net grid imports/exports, GHG emissions reductions (metric tons of carbon dioxide per year), internal rate of return, and payback period.

Financial modeling assumed 1) an Investment Tax Credit of 30 percent base plus 10 percent for energy communities and 10 percent for domestic content, 2) well to gate production tax credit of $0.0312/kWh, 3) Self-Generation Incentive Program of up to $5 million based on capacity and emissions criteria, and 4) NEM 3.0/ACC export and load-offset values based on CPUC's ACC.

The project assumed fully installed capital costs for each individual component as outlined in Table 2.

Table 2: Capital Costs Assumed in Financial Model

Fuel Cell	$1,500	per kW
Hydrogen Storage	$1,000	per kg
Wind	$2,500	per kW
Solar	$1,500	per kW
Electrolyzer	$1,400	per kW

Source: DasH2energy

CHAPTER 3: Results

Alkaline Electrolyzer Performance

Steady State Operations

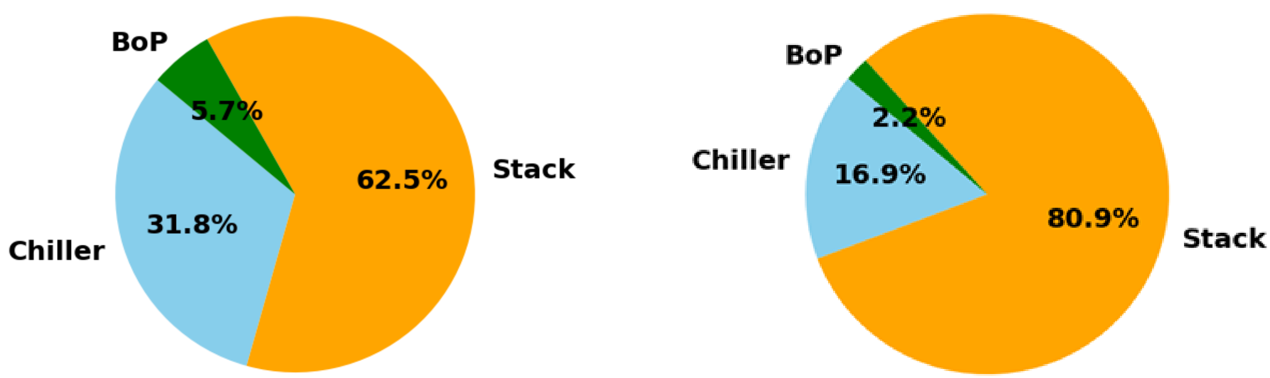
The AEZ was operated at different load conditions to develop a power curve for the model simulation. Table 3 provides a summary of the efficiency of the electrolyzer at the stack level and the system level. The stack efficiency improved at lower partial load, which is consistent with electrochemical properties of electrolysis. However, at lower partial loads the electrolyzer system efficiency decreased due to BoP loads. Figure 11 details the subsystem power consumption at minimum load (left) and maximum load (right).

Table 3: Energy Intensities of Production Subsystem

Production Rate	Stack energy kilowatt hour per kilogram	System energy kilowatt hour per kilogram
34%	48.19	83.82
50%	49.94	79.91
75%	52.66	73.62
100%	56.01	74.05

Source: University of California, Irvine

Figure 11: Subsystem Power Contributions at Minimum and Maximum Load



Source: University of California, Irvine

Cold/Hot Start

Cold start refers to initiating electrolyzer operation from ambient temperature conditions, typically after extended downtime or overnight standby. Hot start, by contrast, refers to restarting the electrolyzer from an elevated temperature, where internal components — particularly the electrolyte and electrodes — are already partially warmed from prior use.

For cold starts, reaching steady-state operation at minimum hydrogen production required approximately 14 minutes, based on stabilization of stack voltage and outlet temperatures at both the anode and cathode. In addition, a 5-minute nitrogen purge was required prior to hydrogen generation, bringing the total cold start time to approximately 19 minutes.

During hot starts, elevated stack temperatures can help accelerate electrochemical activation, potentially shortening the stabilization period. However, data from this project showed temporary instability in current and gas purity during approximately the first 20 minutes following hot restart, likely due to transient effects such as water/gas crossover, residual moisture in the stack, or thermal gradients. While hot start-up may reduce warm-up time, these effects can impact hydrogen purity and system reliability during the initial restart window.

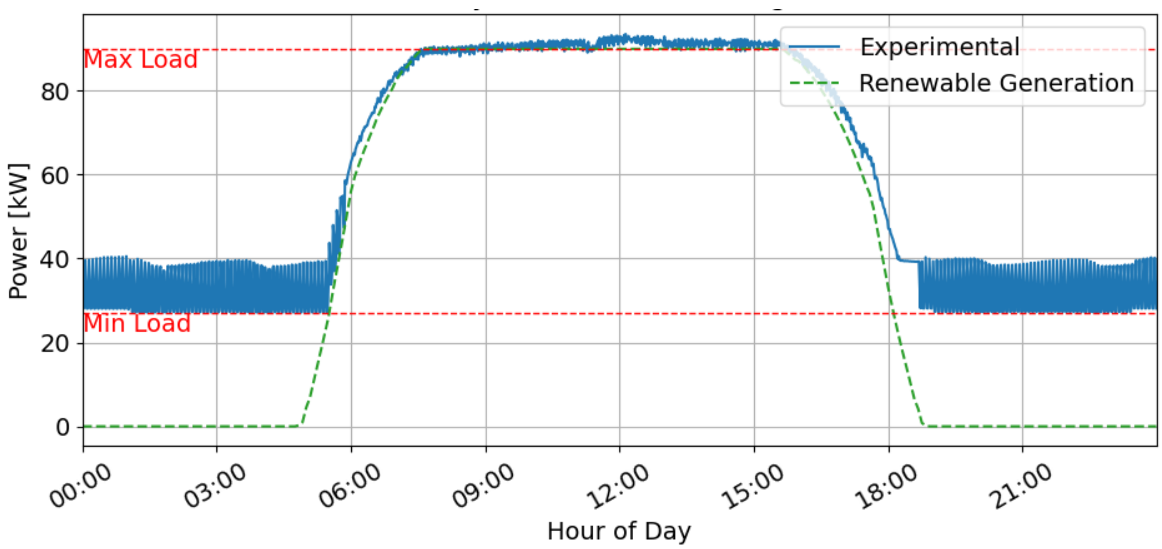
Notably, the time to reach steady-state at maximum production (full hydrogen output) was consistent with the minimum production case — approximately 14 minutes — regardless of whether the system was cold or hot started. This suggests that ramp-up to full power is primarily governed by thermal equilibrium and fluid dynamics, rather than the magnitude of electrical input.

These start-up behaviors are important because hydrogen electrolyzers must often respond to variable renewable energy supply, especially in distributed applications where solar or wind profiles are intermittent. Faster and more stable start-up performance enables the electrolyzer to capture more renewable energy generation during short availability windows (for example, solar ramps), improving system use and economics. Minimizing start-up losses is therefore key to enabling flexible, responsive hydrogen production that complements grid needs and renewable output.

Alkaline Electrolyzer Dynamic Modeling

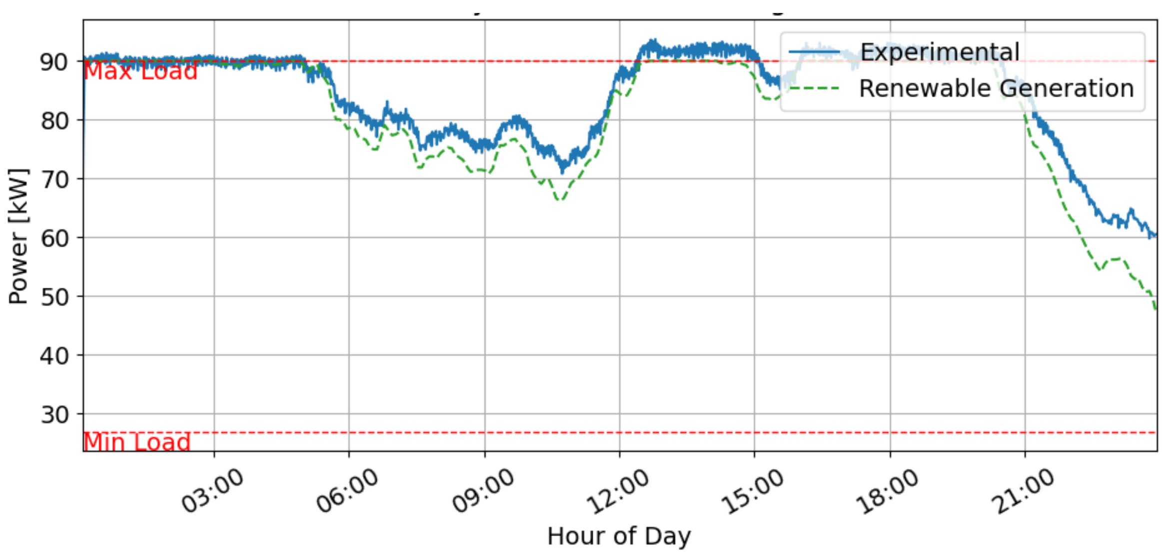
Emulation of dynamic operation following demand and generation profiles taken from PWD was executed by programming a mass flow controller via an external control circuit that controlled the back pressure. The mass flow controller was operating using five different wind and solar profiles as illustrated in Figures 12 and 13, which show real time load following for both wind and solar generation, respectively. While it was originally assumed that the AEZ cannot dynamically operate with renewables, the demonstration showed that the AEZ can manage renewable intermittency up to the minimum load requirement of 34.5 percent.

Figure 12: Electrolyzer Load Matching Following Solar Generation



Source: University of California, Irvine

Figure 13: Electrolyzer Load Matching Following Wind Generation



Source: University of California, Irvine

Proton Exchange Membrane Fuel Cell Performance

Steady State

The PEMFC was operated at different load levels to characterize its performance curve and calibrate the simulation model. Table 4 summarizes the electrical efficiency at both the stack level and the system level, with and without the external chiller.

The term "stack efficiency" in this context refers specifically to the fuel cell's electrochemical conversion performance, excluding BoP. By contrast, "system efficiency" includes all BoP components, such as high-voltage direct current (DC) bus losses, water and hydrogen circulation pumps, fuel cell air compressor, battery emulator, and external chiller (when included in the test scenario). Therefore, when the chiller was excluded from the system, the measured efficiency represented the fuel cell system without thermal management overhead, which still captured key BoP losses. This distinction is important for evaluating integration trade-offs in real-world deployments.

Table 4: Energy Efficiencies of Fuel Cell Subsystem

Power Request [kW]	Stack Electrical Efficiency [%]	System Electrical Efficiency (without chiller) [%]	System Electrical Efficiency (with chiller) [%]
5	56.8	36.7	7.1
25	49.3	41.1	6.4
50	46.1	37.0	18.6

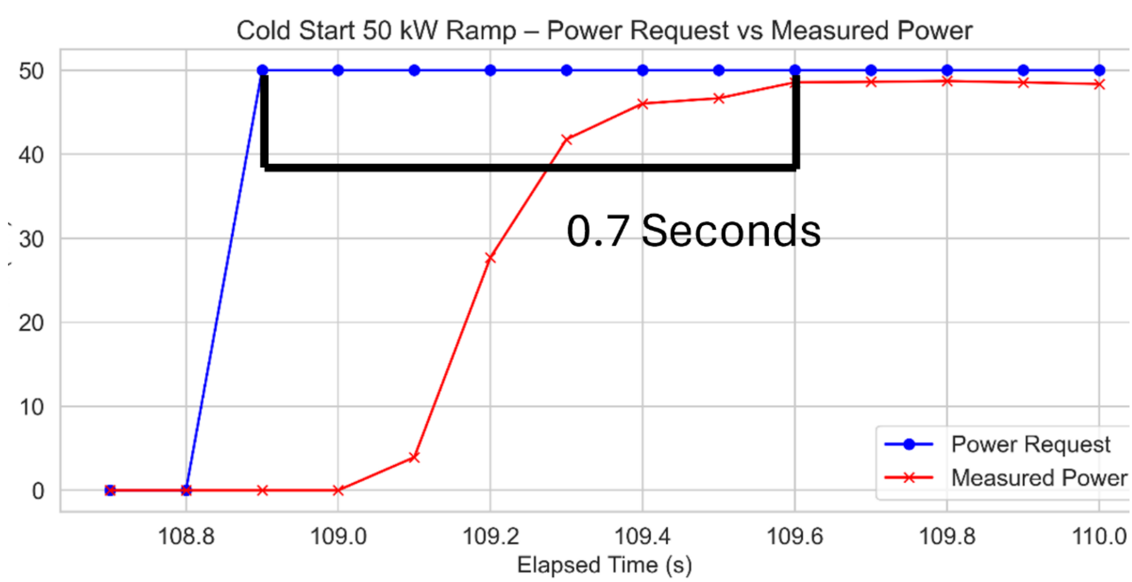
Source: University of California, Irvine

As expected, stack efficiency improved at lower power levels, reflecting the inherent electrochemical behavior of fuel cells, where voltage losses are lower at reduced current densities. However, overall system efficiency decreased at lower loads due to the fixed overhead of BoP components, which become proportionally more significant.

Cold/Hot Start

The cold start test was conducted from a fully shutdown PEMFC and, upon system initialization, a maximum power request was immediately sent. The PEMFC successfully ramped to its rated output in less than one second as shown in Figure 14. This rapid response was sustained for one hour to assess thermal and electrical stability. Following this period, the power request was reduced to 50 percent rated output and maintained for another hour.

Figure 14: Cold Start Ramp Rate



Source: University of California, Irvine

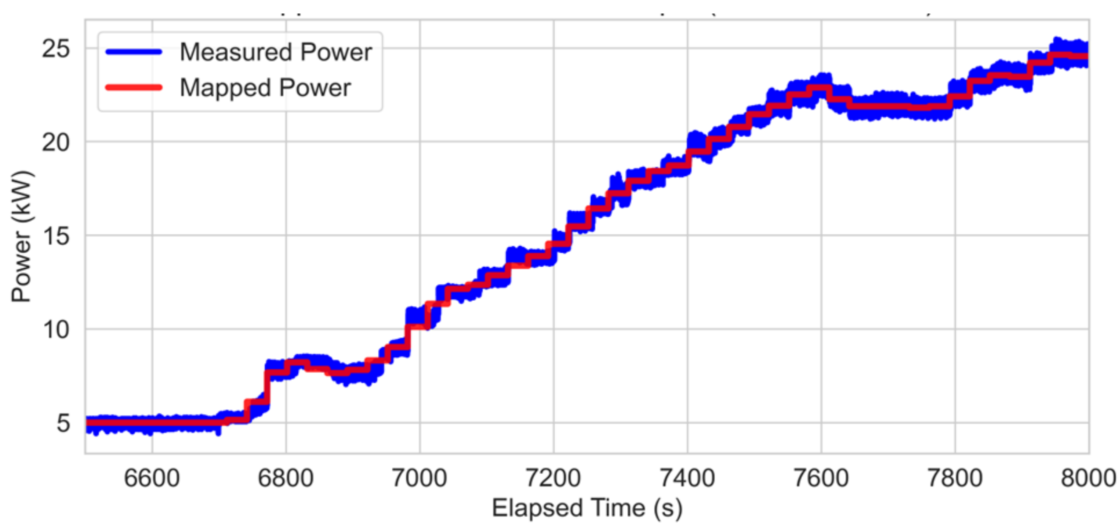
Immediately afterward, a hot start test was performed. The same power ramp-up procedure was applied, with shorter hold times at full power and half power to reduce hydrogen consumption. The PEMFC exhibited the same rapid response as in the cold start test.

Proton Exchange Membrane Fuel Cell Dynamic Modeling

To evaluate the potential of a PEMFC as a dynamic, grid-responsive generator, a series of load-following tests were conducted using dynamic power profiles that inversely followed solar and wind generation patterns. These profiles simulated periods of low renewable output, enabling assessment of the PEMFC's ability to provide grid support by complementing fluctuating renewable sources. Comparison of mapped versus measured results showed close alignment, confirming the PEMFC's capability to effectively track solar generation dips and wind variability based on manually input power profiles.

The PEMFC was also subjected to a time-varying power profile that involved manually programmed stepwise power increases ranging from 5 kW to 25 kW. This range reflects the partial-load operating window typical of distributed grid-support systems. The objective was to determine the responsiveness and tracking accuracy of the PEMFC. Figure 15 below compares the mapped (red line) power input profile with the measured response (blue line) of the PEMFC during the test period for wind generation.

Figure 15: Wind Proton Exchange Membrane Fuel Cell Load Matching



Source: University of California, Irvine

The measured output closely tracks the mapped target, with minimal delay or deviation at each setpoint change. The time window presented in this graph (approximately 6,600 to 8,000 seconds) highlights the step response behavior, but a longer-duration version of the experiment was also conducted and confirmed similar performance trends. This confirms the PEMFC's capability to perform load-following operation with high fidelity, a critical requirement for grid-supportive DER that must complement renewable intermittency either as a stand-alone generator or as part of a hybrid microgrid configuration.

Hydrogen Storage Long-Term Leakage Test

The high-pressure storage tank was tested to determine if there was any leakage or loss of hydrogen, which is critical for hydrogen's ability to provide long duration energy storage. The tanks were filled to rated pressure and then left undisturbed for 12 months under monitored ambient conditions. Hydrogen retention was monitored using thermocouple pressure transducers, which recorded internal pressure readings over time. Because the system remained closed and temperature variations were accounted for, any pressure drop would have indicated gas loss due to leakage.

After one year, no measurable pressure drop was observed within the tolerance of the installed equipment. This result confirmed that the composite storage vessels retained hydrogen effectively, with no detectable leakage, validating their suitability for long-duration applications.

Techno-Economic Analysis and Business Model Design

Evaluating the economic viability of hydrogen-based energy storage systems is just as critical as demonstrating their technical feasibility. Given the high capital costs and evolving incentive structures, it is essential to identify use cases where hydrogen systems provide distinct value. This project used scenario-based modeling to assess five configurations tailored to the PWD site, summarized in Table 5.

Table 5: Business Model Use Case Scenarios

Scenario	Description	Purpose
1. Wind-to-Hydrogen	A 2 MW wind turbine dedicated to hydrogen production and reconversion via fuel cell.	Demonstrates a closed-loop, off-grid hydrogen storage cycle.
2. Wind + Microgrid Controller	Wind used to meet on-site load first; surplus diverted to hydrogen.	Tests load prioritization and smart dispatch capabilities.
3. Hybrid Wind + Solar Microgrid	Combines 1 MW wind with 1 MW solar for integrated generation.	Assesses benefits of generation diversity and interconnection optimization.
4. ACC-Tariff Optimized	Electrolyzer charges during low ACC hours; fuel cell dispatches during high-value periods.	Explores time-of-day price arbitrage using NEM 3.0/ACC signals.
5. Fuel Cell Only	On-site fuel cell assuming low-cost trucked hydrogen.	Models a simple, dispatchable fuel cell approach without on-site production.

Source: DasH2energy

System Efficiency

Starting with the real time experimental data, which demonstrated relatively low RTE of approximately 13 percent, the project identified several optimization strategies — including improved thermal management, right-sized chillers, variable-speed pumps, and partial-load fuel cell operation — that could significantly improve performance. For business modeling purposes, the project assumed an electrolyzer system efficiency of 60 kWh/kg H2 (improved relative to the 74-83 kWh/kg H2 measured at UCI) and a fuel cell system efficiency of 50 percent (improved relative to the 36-37 percent without the chiller measured at UCI). These assumptions yield a projected RTE of 32 percent, which represents a more commercially viable benchmark for evaluating hydrogen-based P2P energy storage systems.

Financial Modeling Results

The results for each scenario are summarized in Table 6, with each delivering a positive internal rate of return while varying in renewable penetration, financial savings, capital cost, and GHG reduction potential.

Table 6: DER Scenario Results

	1	2	3	4	5
Renewable Energy provided to PWD	45%	100%	97%	44%	24%
Financial Savings	$616,992	$742,535	$696,028	$408,280	$230,838
GHG Emissions Reduction, tons of CO2	444	528	510	252	122
Capital Cost	$13.5 M	$13.5 M	$12.7 M	$4.1 M	$4.4 M
Internal Rate of Return	9.5%	10.7%	10.0%	7.10%	13.13%

Source: D2E

Scenario 2 (Wind + Microgrid) emerged as the most balanced option, delivering the highest financial savings and GHG reductions, albeit with a higher capital investment. Scenario 3 (Hybrid Wind + Solar) offered nearly comparable benefits with slightly improved capital efficiency. Scenario 5 (Fuel Cell Only) achieved the highest internal rate of return due to its low upfront cost, but with limited renewable contribution and emissions reductions. Meanwhile, Scenario 4 (ACC Optimization) demonstrated that tariff-responsive dispatch can improve value capture under NEM 3.0, though its performance was moderate across all metrics. Scenario 1 (Wind Only) provided a useful baseline with moderate performance and cost, highlighting the value of integrating controls and hybridization. Collectively, these scenarios illustrate the flexibility of hydrogen systems in achieving diverse energy, economic, and environmental goals.

CHAPTER 4: Knowledge Transfer

This project conducted a range of knowledge transfer activities, including through the project technical advisory committee, hosting site tours at UCI, social media postings, and dissemination of learnings and results at industry and technical conferences. The award played a critical role in enabling these engagements by funding the installation, commissioning, and demonstration of a fully integrated hydrogen P2P system. By operating the system in a real-world university setting, the project allowed stakeholders to observe and interact with the technology in a way that would not have been possible in a lab or paper study. This transparency helped de-risk the technology, validate key performance metrics, and lay the groundwork for follow-on investment.

Technical Advisory Committee

As part of the project, the team convened several technical advisory committee meetings with Panorama Energy Partners on February 14, 2025, and April 18, 2025, and three formal meetings with the Electric Power Research Institute (EPRI) on January 27, 2025, April 29, 2025, and May 21, 2025. Additionally, the team held several informal discussions throughout the project period to evaluate interim results and disseminate key outcomes. These interactions provided a critical platform for technical validation, business model refinement, and strategic guidance.

Electric Power Research Institute

EPRI, through its Low-Carbon Resources Initiative, is advancing foundational research across a range of low-carbon electric generation technologies and chemical energy carriers — such as clean hydrogen, bioenergy, and renewable natural gas — to support cost-effective pathways toward economy-wide decarbonization. Through the technical advisory committee, EPRI made a number of recommendations for the project and for future research, including the need to 1) conduct long-term operational and degradation analyses, 2) examine any power quality impacts of P2P systems, 3) define standardized testing conditions for P2P components, 4) analyze electrolyzer efficiency versus temperature and quantify system loads (for example, chillers) under flexible and steady operation, 5) define hydrogen purity monitoring protocols and operational limits based on current density effects, 6) assess fuel cell system sizing, especially why efficiency peaks at approximately 50 percent load, and 7) apply PEMFC degradation data to guide P2P system flexible and part-load operation strategies.

Panorama Energy Partners

Panorama is a boutique energy consulting firm that offers strategic and analytical support across the energy sector, with a focus on emerging technologies, project development, commercialization, due diligence, market design, and growth strategies. Drawing from its experience with first-of-its-kind projects, Panorama contributed key insights into how to improve project bankability and reduce specific forms of risk.

Technology Risk

First-of-its-kind projects often lack operating history. Panorama noted that actual system performance deviated from vendor specifications. Panorama supported the development of tools to better model system performance across variations in temperature, pressure, and part load. Specific recommendations included 1) extending dynamic testing of the electrolyzer and fuel cell under real-world load cycles, 2) validating electrochemical models using long-duration longitudinal datasets, 3) improving model sensitivity to ambient temperature, chiller efficiency, and pressure drops, and 4) enhancing model predictive accuracy for hydrogen production and efficiency under variable renewable inputs. These enhancements collectively aim to improve forecasting accuracy and reduce technology performance uncertainty in future deployments.

Execution Risk

The project experienced commissioning delays, integration challenges, and incomplete vendor documentation. Panorama emphasized that such issues could compromise commercial projects and recommended 1) developing standardized technical specifications for subsystems, 2) creating detailed commissioning protocols for subsystems and the overall P2P system, and 3) defining clear vendor performance and documentation requirements early in procurement. These measures will support interoperability and reduce implementation risk in future deployments.

Commercial and Market Risk

Panorama highlighted that the lack of verified data hampers financial modeling. The P2P project addressed this gap by generating empirical evidence — validating round-trip efficiency and system operability — that supports due diligence and helps attract future investment. Panorama noted the lack of clear market pathways for hydrogen-based energy storage and recommended targeting community choice aggregations (CCAs) and load serving entities (LSEs) as strategic offtakers.

A proposed structure involves the CCA acting as an intermediary — signing energy savings, demand response, or resource adequacy (RA) contracts with the hydrogen system developer. In this model, the customer may be a commercial or industrial user or the CCA's residential ratepayer base. These contracts would compensate developers for providing dispatchable capacity, load reduction, or backup services, thereby creating a pathway for hydrogen systems to participate in RA markets. Panorama confirmed that CCAs and LSEs can contract for RA, and that this market linkage could help hydrogen systems to scale.

Knowledge and Technology Transfer Activities

The project facilitated meaningful knowledge and technology transfer through a series of activities that conveyed real-world insights on system configuration, RTE, economic modeling, and policy considerations, thereby creating an interactive forum for both technical learning and strategic dialogue.

Over the course of the project 24 technical site tours were conducted, with attendees including CCAs, CEC staff, Alliance for Renewable Clean Hydrogen Energy Systems (ARCHES) representatives, private investors, academics, and municipal utility planners. The tours proved particularly valuable for building market confidence in hydrogen P2P systems by providing visitors with a real-world, hands-on opportunity to observe subsystems and controls and ask operational questions.

Additionally, project findings were shared through seven industry presentations, including at the California Community Choice Association Annual Conference (2023), California Hydrogen Leadership Summit (2023), Hydrogen Americas Summit (2023), Advanced Clean Transportation (ACT) Expo, Energy Storage North America, and Hydrogen and Fuel Cell Seminar (2025).

The project's outreach campaign also included regular updates through LinkedIn, generating more than 34,000 impressions and several hundred engagements. These communications significantly increased visibility with potential partners and led to inquiries from utilities, clean tech investors, and other applicants to the U.S. Department of Energy's Hydrogen Hub program.

These outreach and demonstration efforts directly helped D2E secure its role in the ARCHES Hydrogen Hub, where it was awarded funding for a 20-megawatt resource adequacy project in partnership with Lancaster Choice Energy. Additionally, connections formed during the UCI demonstration enabled collaborations with hydrogen compression and distribution vendors, helping shape joint development agreements for future projects.

Looking forward, D2E is advancing several commercial initiatives in addition to Lancaster including the following.

- Design of modular behind-the-meter hydrogen systems for school districts and water agencies, with the first 2,500 kilowatts planned for deployment in 2026
- Design of distributed front of the meter fuel cell systems, with 9 megawatts being deployed in 2027
- Collaboration with CCA partners to develop resiliency-focused fuel cell projects
- Feasibility assessments for green hydrogen microgrids

These next steps aim to transition hydrogen energy storage from pilot demonstrations to commercial deployments by replicating lessons learned from this project and scaling integrated system architectures in real-world customer applications.

UCI's Role and Legacy

The University of California, Irvine provided key technical support throughout the project. All installed hardware — including the electrolyzer, compressor, and storage tanks — will be donated to UCI for continued research and educational use. This ensures that the knowledge generated from the project will continue to support hydrogen innovation beyond the formal project.

CHAPTER 5: Conclusion

Key Lessons Learned

Through system installation, dynamic testing, electrochemical modeling, and stakeholder engagement, the project generated several key lessons for future hydrogen energy storage deployments. These findings inform both system design and business model development for scaling P2P systems in California and beyond. Key lessons and opportunities for future advancements are described below.

Dynamic Operations of P2P Systems

The project demonstrated that both the AEZ and PEMFC were able to operate dynamically based on variable renewable generation and electricity demand; however, in practice there are limitations based on the amount of time it takes for systems to start up. Key findings include the following.

- Dynamic Operation: Real-time load-following tests showed that the AEZ could modulate hydrogen production down to its minimum stable load of 34.5 percent, while the PEMFC could track fluctuations in power demand and generation within seconds, validating their suitability for renewable-integrated microgrids.
- Start-Up Constraints: While both systems responded well once operational, start-up dynamics did affect flexibility.
    - Cold Start: The AEZ required approximately 14 minutes to reach stable operation, plus 5 minutes for nitrogen purging, limiting its ability to respond to fast-start events from a completely off state.
    - Hot Start: Though faster, hot starts still exhibited gas purity variations and voltage instability during the first 20 minutes, which can affect hydrogen quality and short-term responsiveness.

These start-up constraints suggest that hydrogen systems are better suited for intra-day or hourly variability, but less appropriate for minute-scale frequency regulation unless maintained in standby or warm conditions. Future systems may benefit from hybrid configurations, such as pairing hydrogen with battery storage for immediate response, while leveraging hydrogen's superior ability to store energy for long durations and provide dispatchable power.

Thermal Management

Thermal management emerged as a critical system-level constraint that significantly influenced RTE, component lifespan, and control complexity. Key findings include the following.

- Operating Temperature Ranges: Electrolyzers and fuel cells have narrow optimal temperature bands (for example, 140 degrees Fahrenheit [°F] [60 degrees Celsius

{°C}] to 176°F [80°C]). Exceeding these thresholds leads to membrane degradation, reduced efficiency, and in extreme cases, irreversible stack damage. Maintaining stable thermal conditions is essential for preserving both performance and durability.

- Chiller Sizing: Initial deployment used oversized chillers, which introduced significant parasitic electrical loads, reducing system RTE by an estimated 5 to 15 percent. Future designs should rightsize chillers and enable dynamic control to match thermal loads to system demand and ambient conditions.
- Hybrid Cooling: The project tested a combination of passive heat sinks, closed-loop liquid cooling, and variable-speed chillers, which together provided more efficient and responsive thermal regulation under fluctuating loads.
- Thermal Coupling: Where possible, co-locating the heat loops of the fuel cell and electrolyzer allowed for shared thermal infrastructure and avoided unnecessary redundancy — particularly during partial-load operation or standby conditions.
- Waste Heat Use: While not implemented in this demonstration, future systems should incorporate waste heat recovery to improve overall system efficiency. Recovered heat from the fuel cell, at approximately 140°F (60°C) to 158°F (70°C), or the electrolyzer can potentially be used for preheating electrolyzer water, regenerating desiccants or drying produced hydrogen, driving low-grade thermal processes such as absorption chillers in hot climates, or even building space or water heating. Capturing and reusing thermal energy can boost systemwide efficiency beyond electrical RTE, aligning with U.S. Department of Energy goals for high-efficiency hydrogen systems and supporting broader value propositions for hydrogen in facility or campus energy systems.

Programmable Logic Controller and Controls Integration

The demonstration project highlighted the importance of programmable logic controller (PLC) integration for safe, efficient, and coordinated operation of P2P systems. Key insights include the following.

- Component-Level Control Architecture: Each major subsystem — electrolyzer, compressor, chiller, hydrogen storage, and fuel cell — required independent PLCs, which lacked a unified supervisory controller. This necessitated the development of custom logic and communication protocols to coordinate system functions and sequencing.
- Need for Unified Supervisory Control: The project identified the future need for a centralized PLC or supervisory control and data acquisition (SCADA) architecture to manage multi-device synchronization, load following, safety interlocks, and operational transitions (for example, start-up, shutdown, fault response). Without centralized coordination, system responsiveness and reliability are limited.
- Instrumentation Gaps: Several key components — especially BoP equipment such as chillers, compressors, and inverters — lacked dedicated metering and telemetry. Future deployments should ensure all subsystems are equipped with power meters,

temperature sensors, and flow measurement devices to support full system diagnostics and performance analysis.

- Remote Monitoring Requirements: Real-time remote monitoring was not standard on most off-the-shelf components, requiring additional hardware and software integration. Cloud-based monitoring dashboards and alarm protocols will be critical for commercial systems, particularly for distributed installations with limited on-site staffing.

Together, these findings suggest that controls integration is a major enabler of future hydrogen system scalability and should be addressed early in the design process. Controls standardization across manufacturers remains a challenge and represents a key area for industry-wide coordination.

Design Optimization

The project explored design strategies to enhance system performance, including operating the electrolyzer and fuel cell at partial load to optimize electrochemical efficiency. While stack-level efficiency (voltage efficiency) improves at lower current densities — particularly in PEMFC — this must be balanced against system-level inefficiencies introduced by oversized BoP components such as chillers, pumps, and compressors. Key takeaways include the following.

- Electrochemical Performance: At partial load, both the alkaline electrolyzer and PEM fuel cell demonstrated higher voltage efficiency, reducing energy consumption per kilogram of hydrogen produced or consumed.
- System-Level Tradeoffs: However, operating oversized systems at part load can lead to underuse of fixed-load BoP equipment, such as oversized chillers or constant-speed pumps. These parasitic loads are not scaled proportionally, resulting in lower overall system efficiency.
- Rightsizing versus Oversizing: The project found that moderate oversizing of the electrolyzer and fuel cell may still offer benefits, particularly for load-following and thermal stability, but it must be carefully balanced with dynamic BoP sizing (for example, using variable-speed drives, modular chillers, or staged compressors) to avoid reducing the RTE.
- Design with vendor alignment: Engage vendors early to align fuel cell, electrolyzer, and balance-of-plant design with P2P system-level use cases, including flexible dispatch, remote control, and maintenance-free idle time.

The project team's experience suggests that hybrid optimization approaches — using electrochemical models to find the optimal tradeoff between stack efficiency and system parasitic loses — are critical. Future systems should also consider thermal coupling and heat reuse to offset BoP losses, as mentioned above, when operating at partial load.

Business Model Alignment

Hydrogen P2P systems, while currently limited by relatively low RTE, present compelling business model advantages, particularly for BTM deployments with limited ability to export. Unlike lithium-ion batteries that are generally limited to 4-8 hours, hydrogen systems can economically store much larger volumes of energy over longer durations. Additionally, hydrogen does not suffer from self-discharge typical for lithium-ion systems and is able to scale energy and power independently. Finally, a well-designed PEMFC system can remain idle for extended periods without maintenance and can ramp to full power almost instantaneously; thus, they are well suited for applications where availability, not use, is the primary value. These attributes suggest business models focused on low use but high reliability, such as critical facility backup power, seasonal energy shifting, monthly peak shaving, and capacity reserve, are well-suited for P2P systems.

To help encourage market development for hydrogen P2P systems and appropriately value their unique attributes, future cost-benefit assessments should prioritize capacity value, resilience, and avoided outage costs, rather than rely solely on $/kWh metrics. Additionally, development of tariffs and/or incentive programs that recognize and compensate long-duration storage and dispatchability should be considered.

Recommendations for Future Research and Improvement

This project identified several areas where further research and technology development are needed to support commercialization of hydrogen P2P systems, including targeted degradation testing, controls optimization, and commercial development of purpose-built stationary fuel cells for electric sector applications.

Degradation Testing

Long-term degradation data for dynamically operated alkaline electrolyzes and fuel cells is limited and future research should address the following gaps.

- Dynamic cycling degradation studies to understand how real-world, variable load profiles affect degradation versus steady-state operation. Develop and implement standardized dynamic load profiles across multiple duty cycles while monitoring performance decay in terms of voltage degradation, efficiency loss, and hydrogen purity drift.
- Temperature-accelerated lifetime testing to quantify degradation at elevated stack temperatures (176°F [80°C] to 194°F [90°C]), which could support high-efficiency designs. Compare degradation rates across multiple operating temperatures coupled with thermal cycling tests to simulate daily ramping and cooldown effects.
- Start-stop and idling effects to quantify how frequent start-stop or idling behavior, which would be common in P2P applications, impacts stack longevity by introducing periodic start-up/shutdown cycles with variable ambient conditions, while evaluating failure modes like electrolyte leakage, catalyst delamination, or membrane shrinkage.
- Degradation under sustained variable ramping with variable renewable generation to evaluate how real solar/wind generation profiles affect stack health by using historical renewable energy data to simulate variable current density and ramping rates. Track stack efficiency, heat buildup, and pressure variations for sustained durations of variable ramping following renewable generation profiles.

- Real-time degradation diagnostics with low-cost, deployable tools to detect degradation before catastrophic failure. Design algorithms with artificial intelligence for anomaly detection using stack voltage, impedance, and temperature profiles integrated with SCADA/PLC systems for predictive maintenance alerts.

Controls Optimization

Compared to traditional microgrids, which typically operate on a daily dispatch cycle to balance variable renewables and load, hydrogen-based systems introduce unique temporal and operational dynamics. In particular, the storage and conversion characteristics of hydrogen require multi-day to monthly balancing to optimize both energy yield and storage use. These time frames pose new challenges for traditional microgrid controllers and warrant a broader research focus on system-level integration and advanced control architectures for P2P systems. Key areas for future research and technology improvement include the following.

- Integrated System Controller: Hydrogen systems often comprise independently operated subsystems — electrolyzer, compressor, hydrogen storage, and fuel cell — each with separate PLCs and operational logic. Future research should focus on a centralized supervisory control system that can coordinate these PLCs for optimized performance across timeframes spanning minutes to months.
- Advanced Dispatch Optimization: Controls should incorporate load forecasting, DER generation prediction, and energy price signals (for example, from ACC or RA markets) to perform optimal dispatch decisions that align with long-duration storage value streams.
- Energy and Thermal Management: Real-time monitoring and adaptive control of chiller loads, stack temperatures, and ambient conditions could be used to improve RTE while coordinated thermal management between the electrolyzer and fuel cell subsystems could reduce redundant cooling needs.
- Stack Performance at Higher Temperatures: While most commercial electrolyzers and fuel cells operate around 140°F (60°C) to 158°F (70°C), research suggests that operating at higher temperatures (176°F [80°C] to 194°F [90°C]) can improve reaction kinetics and stack efficiency. However, this requires careful thermal control and materials evaluation, especially to avoid degradation. The recommendation is valid but may need further qualification (for example, applicable to certain alkaline or PEM systems under controlled conditions).
- Direct DC Integration: Supplying DC power from renewable sources directly to the electrolyzer would avoid unnecessary DC-AC-DC conversions, reducing power electronics losses and improving overall system efficiency.
- Data Logging and Performance Validation: High-resolution monitoring is essential for validating system behavior under dynamic conditions. Controllers should support synchronized logging across subsystems to enable techno-economic validation and support future bankability.

Purpose Built Stationary Fuel Cells for Electric Power Generation

Most commercially available PEMFC are designed for heavy-duty transportation applications, including trucking, marine, and aviation. These use cases prioritize power density, weight reduction, and fast ramp rates — features that add cost and complexity but are unnecessary for stationary, BTM, or grid-tied power systems.

For stationary applications, PEMFCs operate under intermittent, partial load, or extended idle conditions. As demonstrated in this project, such systems require simplified thermal and BoP design, optimized stack performance at partial load, and reduced cost per installed kW, rather than energy density. Future vendors should develop stationary-optimized PEMFC systems tailored for grid applications, with fewer moving parts, lower system complexity, and configurations suited for reliability, load following, and flexible dispatch rather than continuous high-power output. By aligning design philosophy with actual dispatch behavior, vendors can improve system economics, reliability, and lifecycle cost-effectiveness — making hydrogen P2P systems more bankable and better suited for grid-integrated deployments.

Benefits to California Ratepayers

This project successfully designed and developed an integrated hydrogen P2P system and evaluated the system cost and benefits in a customer side of the meter application. In BTM applications, P2P systems can allow larger deployment of distributed generation without increasing export onto the distribution grid. Additionally, hydrogen produced during low-cost times can be stored for long periods and then reconverted into electricity during periods of grid stress or high generation costs. This flexibility can help balance renewable generation and demand over long periods of time, providing the benefit of increased reliability. Hydrogen P2P systems could provide a zero-carbon firm resource, allowing the state to achieve SB 100 goals at a lower total cost compared to other scenarios considered in the study.

GLOSSARY AND LIST OF ACRONYMS

Term	Definition
AC	alternating current
ACC	Avoided Cost Calculator - a tool used to determine the potential savings a utility can achieve by avoiding certain costs associated with providing electricity or other services
AEM	anion exchange membrane - a type of water electrolyzer that uses a semipermeable membrane to separate the anode and cathode compartments while allowing hydroxide ions to pass through
AEZ	alkaline electrolyzer - the equipment used to convert water into hydrogen with direct current electricity
ARCHES	Alliance for Renewable Clean Hydrogen Energy Systems - a public-private partnership focused on developing a renewable hydrogen hub in California
BoP	balance of plant - the supporting systems and infrastructure necessary for efficient operation, excluding the primary generating or process equipment
BTM	behind the meter - energy systems and activities that occur on the consumer's side of the electric meter
°C	degrees Celsius
CARB	California Air Resources Board - a California state agency that focuses on reducing air pollution and addressing climate change. Its primary goal is to protect public health, welfare, and ecological resources by minimizing air pollutants, setting air quality standards, identifying harmful pollutants, measuring progress in reducing emissions, and verifying automakers' compliance
CCA	community choice aggregation - load serving entities that procure electricity on behalf of retail electricity customers within some geographic areas
CEC	California Energy Commission - the California state agency responsible for energy policy
CPUC	California Public Utilities Commission - a regulatory agency that regulates privately owned public utilities in California, including electric power, telecommunications, natural gas, and water companies
D2E	DasH2energy - principal investigator and lead project developer of this work
DAQ	data acquisition system - a system used for acquiring, storing, visualizing, and processing data
DC	direct current
DERs	distributed energy resources - small-scale energy generation and storage systems located close to where the electricity is used, rather than at a central power plant

Term	Definition
DI	deionized water - water that has had all of its mineral ions removed
EPIC	Electric Power Investment Charge - program invested in scientific and technological research to accelerate the transformation of the electricity sector to meet California's energy and climate goals
EPRI	Electric Power Research Institute - an independent, non-profit research and development organization that focuses on advancing the electricity industry. It conducts research, develops technologies, and provides knowledge transfer to help ensure the public has clean, safe, reliable, affordable, and equitable access to electricity.
°F	degrees Fahrenheit
FTM	front of the meter - energy generation and storage facilities that are connected to the electricity grid on the utility side of the customer's meter
GHG	greenhouse gas - gases in the atmosphere that absorb and emit infrared radiation, trapping heat and contributing to the greenhouse, or warming, effect
H2	hydrogen - a chemical element
kg	kilogram - a unit of mass
kW	kilowatt - a unit of power, specifically used to measure electrical power
kWh	kilowatt-hours
kWh/kg	kilowatt-hours per kilogram - a unit used to express energy density, specifically the amount of energy
LDES	long duration energy storage - technologies that can store energy for extended periods, typically 10 hours or more
LSE	load serving entity - an entity, such as a company or government agency, that is legally obligated to provide electricity to end-use customers
M&V	measurement and verification - a document that details how the project will measure and verify data collection
NEM	net energy metering - a billing system in which customers with eligible renewable energy systems (like solar panels) receive credits for the electricity they send back to the utility grid when their system produces more power than they use
NFPA	National Fire Protection Code - United States-based international nonprofit organization devoted to eliminating death, injury, property damage, and economic loss due to fire, electrical, and related hazards
P2P	power-to-power - the process of using power to create hydrogen for storage and that is later converted back to power
PEM	proton exchange membrane

Term	Definition
PEMFC	proton exchange membrane fuel cell - electrochemical device that converts hydrogen fuel into power
PLC	programmable logic controller - an industrial computer designed to automate manufacturing processes and control machinery
PWD	Palmdale Water District - the commercial and industrial customer on which this project was based
RA	resource adequacy - the ability of an electric system to meet the power demands of its customers under all conditions, including peak demand and potential outages
RTE	round-trip efficiency - an energy storage system with the ratio of the total energy output by the system to the total energy input to the system, as measured at the point of connection
SCADA	Supervisory Control and Data Acquisition - a system of software and hardware that allows organizations to monitor and control industrial processes
SCE	Southern California Edison - an investor-owned utility company that provides electricity to Southern California
Self-Generation Incentive Program	a California program that offers incentives for installing renewable energy and energy storage systems that can function during power outages
TESI	Teledyne Energy Systems, Inc - private engineering company for the hydrogen energy storage system
TOU	time-of-use
UCI	University California, Irvine - site host for this project
WTG	wind turbine generator - a machine that turns wind energy into electricity using the aerodynamic force from the rotor blades, which work like an airplane wing or helicopter rotor blade

References

California Public Utilities Commission (CPUC). 2024. "DER Cost Effectiveness." Available at https://www.cpuc.ca.gov/industries-and-topics/electrical-energy/demand-side-management/energy-efficiency/der-cost-effectiveness.

Project Deliverables

Project Deliverables including interim project reports, are available upon request by submitting an email to pubs@energy.ca.gov. Below is a bulleted list of the products produced — primarily the deliverables noted in the key technical tasks.

- Energy Analysis Report (D211)
- Conceptual System Design Report (D221)
- Preliminary System Design Report (D231)
- CPR Report #1 (D132)
- System Detailed Design Report (D301)
- Safety and Training Report (D401)
- System Commissioning Report (D501)
- D133 CPR Report #2 (D134)
- System Performance and Optimization Report (D601)
- M&V Plan (D702)
- M&V Report final (D704)
- Final Meeting Benefits Questionnaire (D803)
- Final Project Fact Sheet (D903)
- Presentation Materials (D906)
- Technology/Knowledge Transfer Plan (D909)
- Technology/Knowledge Transfer Report (D911)