CALIFORNIA ENERGY COMMISSION

CALIFORNIA NATURAL RESOURCES AGENCY

ENERGY RESEARCH AND DEVELOPMENT DIVISION

FINAL PROJECT REPORT

Ultra-high Efficiency, Lower-Cost, Green Electrolytic Hydrogen for Microgrids in California

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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 and 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.

Ultra-high Efficiency, Lower-Cost, Green Electrolytic Hydrogen for Microgrids in California is the final report for the Ultra-high Efficiency, Lower-Cost, Green Electrolytic H2 for Microgrids project (Contract Number: EPC-19-044) conducted by T2M Global. 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

Long-duration energy storage solutions are needed to maximize the value of California’s renewable electricity. Senate Bill 1369 (Skinner, Chapter 567, Statutes of 2018) identified the potential for green electrolytic hydrogen to decrease grid integration costs and reduce pollution. Conventional water electrolysis systems coupled with hydrogen fuel cells are less efficient than lithium-ion batteries at storing electricity. The round-trip efficiency of conventional hydrogen energy storage, combined with high initial capital costs, is a barrier to entry into established energy storage markets. Under this grant, the T2M Global team developed and validated an alternate solution for green electrolytic hydrogen energy storage at a kilowatt-class level. The experimental results validated under this research project predict that an Advanced Electrolyzer System could achieve a round-trip electrical efficiency for storage of more than 80 percent. By comparison, conventional water electrolyzer systems have a round-trip efficiency closer to 40 percent. This high round-trip electrical efficiency was attained by eliminating high parasitic losses associated with the co-production of oxygen. It also reduces overall system capital cost while increasing its durability. The T2M Global project team attained their project goal and developed designs for a 100-kW-class Advanced Electrolyzer System building block that could be combined into a larger long-duration energy storage system. The Advanced Electrolyzer System technology has the potential to compete with lithium-ion batteries, especially in long-duration energy storage applications. The Advanced Electrolyzer System enhanced safety features and flexible integration with various stranded resources make the Advanced Electrolyzer System technology especially suitable for deployment in California’s disadvantaged communities.

Keywords: California Energy Commission, long-duration energy storage, green hydrogen, Advanced Electrolyzer System

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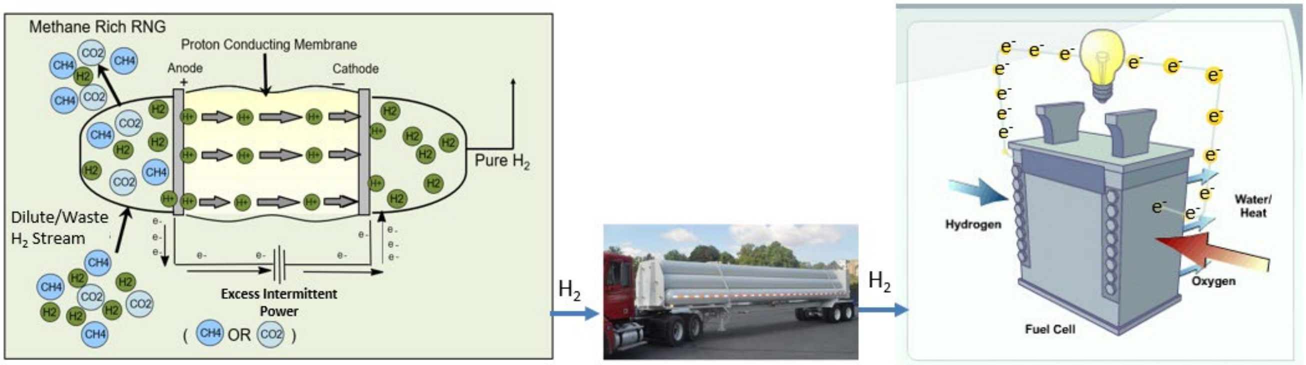
Background

Problem: Long-duration energy storage solutions are needed to maximize the value of California's renewable electricity. The Pacific Gas and Electric's Research and Development Strategy Report of June 2023, identifies that "effectively evaluating and deploying next-generation energy supply and storage technologies is essential to achieving PG&E's goal of a net zero energy system by 2040." Conventional lithium-ion battery storage is prohibitively expensive in LDES applications. Senate Bill 1369 (Skinner, Chapter 567, Statutes of 2018) identified the need for green electrolytic hydrogen as a potentially lower cost and synergistic solution; however, conventional water electrolysis systems have a round-trip efficiency of less than 40 percent and are capital intensive, making deployment in the energy storage market less viable. A lower-cost, competitive option for energy storage is needed for deployment in California, especially in disadvantaged communities. While water is an abundant resource for hydrogen, to extract hydrogen from water requires 50 kilowatt hours per kilogram (kWh/kg) of hydrogen. About 40 kWh/kg of this electricity is associated with the co-product oxygen Alternate hydrogen carriers not involving oxygen co-production offer a promising pathway for cost-effective energy storage to meet the Senate Bill 1369 mandate requirements.

Solution: T2M Global has identified alternate hydrogen carriers that are oxygen-free, promising 80 percent less electricity use for energy storage applications. The Advanced Electrolyzer System for extracting H2 from waste/dilute streams doubles the round-trip electrical efficiency of conventional water electrolyzer systems (from less than 40 percent to more than 80 percent), while reducing the capital cost by approximately 50 percent. These benefits are achieved by eliminating high electrical losses associated with the co-production of oxygen and reducing the use of associated precious metals. Electrolysis of dilute/waste hydro-gen streams provides dual benefits: producing lower-cost hydrogen for energy storage with no increase in greenhouse gas footprint—to achieve decarbonization goals. Figure ES-1 illustrates the developed Advanced Electrolyzer System-hydrogen system concept. Abundant resources of dilute hydrogen streams include tail gases from biomass/waste gasification, liquid biofuels, biogas-fueled reformers, pyrolysis reactors, wastewater treatment plants, fuel cells, etc.

Figure ES-1. Cost Effective Energy Storage – AES-H2 Technology



Charging Cycle (Protonic) | H_2 Storage (Gaseous) | Discharge Cycle (Fuel Cell)

Protonic cycle promises greater than 80 percent round-trip efficiency for energy storage with enhanced safety.

Source: T2M Global

Project Purpose and Approach

The overall objectives for this project were to:

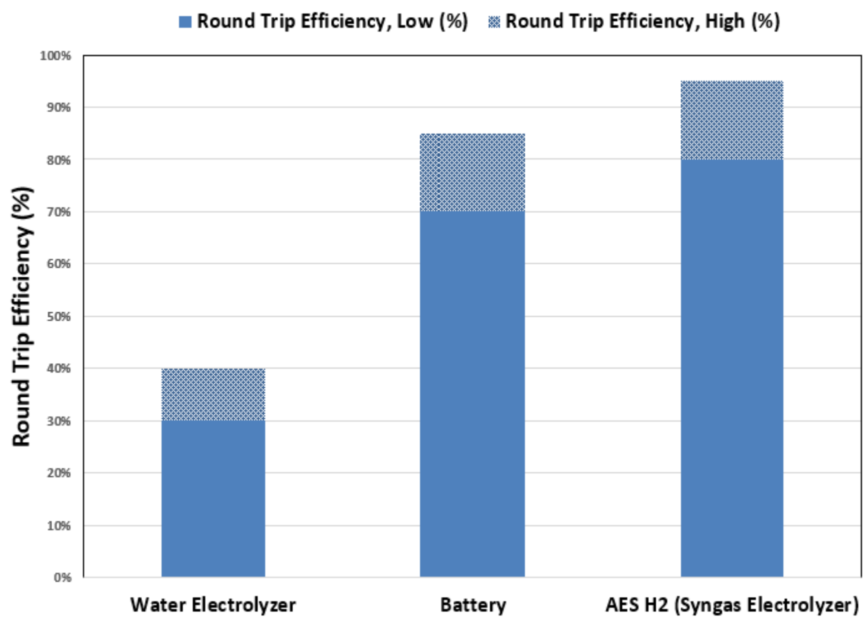
- Validate kilowatt (kW)-class Advanced Electrolyzer System-hydrogen Energy Storage System—more than 80 percent efficiency.
- Analyze waste/dilute hydrogen streams available in California for energy storage.
- Validate Advanced Electrolyzer System flexibility on a variety of feedstocks from different market segments.
- Develop a 100-kilowatt building block design for deployment in California.
- Perform technoeconomic analysis to produce hydrogen at less than $4/kilogram.
- Estimate benefits to California stakeholders, investor-owned utility ratepayers, disadvantaged communities, low-income communities, and environmental justice communities, and perform outreach activities.

Key Results

- Met and exceeded the target of 80 percent efficiency for electrolytic hydrogen energy storage (Figure ES-2).
- Reduced the electricity consumption by 80 percent compared to water electrolyzers.
- Operated the Advanced Electrolyzer System under a variety of market conditions for over 2,000 hours.
- Successfully scaled up and validated Advanced Electrolyzer System by 25 times, from less than 0.2 to 5 kilograms per day.
- Developed 100-kilowatt class energy storage building block for California microgrid support.

- Surveyed over a dozen California sites as early adopters for Advanced Electrolyzer System deployment.
- Estimates show dilute/waste hydrogen streams have a cumulative potential of over 20,000 gigawatt hours per year energy storage for Advanced Electrolyzer System to support California needs.
- Validated Advanced Electrolyzer System potential to produce hydrogen at less than $4/kilogram at scale.
- Identified pathway to a levelized cost of storage of less than five cents/kilowatt hour.
- Used guidance from the technical advisory committee and investor-owned utilities to identify early adopters for Advanced Electrolyzer System-hydrogen storage.
- Increased Advanced Electrolyzer System technical readiness level from four to six.

Figure ES-2. Competitive Landscape—Energy Storage Efficiency



Advanced Electrolyzer System achieves highest electrical efficiency: greater than 90 percent.

Source: T2M Global

Potential Benefits to California Ratepayers

The analyses of Advanced Electrolyzer System data for electrolytic hydrogen energy storage show over 20 gigawatt-hours per day electricity storage potential in California. The resultant benefits of enhanced grid reliability to California ratepayers, investor-owned utilities, and other stakeholders, such as disadvantaged communities and Environmental Justice communities, are:

- The curtailment savings are estimated to exceed $1.2 billion per year to ratepayers.
- More than $300 million per year curtailment savings to Independently Owned Utilities by eliminating payments to other states and purchase of expensive electricity during shortages in the evenings.

- The reduced use of fossil fuels for managing peak demand is expected to reduce greenhouse gas emissions by 2.66 million tons per year.
- The deployment of Advanced Electrolyzer System-hydrogen in higher priority communities could create over 2,000 well-paying jobs and improve quality of life due to healthier environments and better air quality.

Knowledge Transfer and Next Steps

The T2M team successfully performed extensive outreach to major stakeholders and technical advisory committee members to develop market responsive Advanced Electrolyzer System technology and its deployment strategy in California. The following knowledge transfer partners and activities provided valuable guidance:

- Strategic Alliances: Pacific Gas and Electric, Southern California Gas; California Independent System Operator; California universities; South Coast Air Quality Management District.
- Sponsoring Agencies: Department of Energy, Department of Defense, California Energy Commission, California Air Resources Board, Electric Power Research Institute, GTI Energy, Ports, California Highway Patrol centers.
- Investment Partners: Private and public sponsors.
- Demonstration Partners: Identified potential early adopters in California.
- Microgrid Market Partners: Electric vehicle charging, aggregators, and gas industry.
- Supply Chain: Manufacturing of cell, stack, and system components in California.
- Conferences: CleanTech Open, VERGE Energy, Shell GameChanger Accelerator Powered by National Renewable Energy Laboratory, Department of Energy Advanced Manufacturing Office, California Energy Commission Electric Power Investment Charge.
- Trade Associations: California Hydrogen Business Council, California Bioenergy.

Next Steps: Pathway and Timeframe to Commercialization

- Energy Storage Scale-up: 2.4 megawatt hours per day, 100 kW-class Advanced Electrolyzer System building block; 2024 – 2025.
- Pilot Demonstration: Enhance resiliency of microgrid using Advanced Electrolyzer System-hydrogen; 2025 – 2026.
- Prototype Demonstration of megawatt-class Advanced Electrolyzer System module; 2026 – 2027.
- Manufacturing Plant Development: Advanced Electrolyzer System-hydrogen megawatt-class module assembly; 2024 – 2027.
- Seeding in Niche Markets: early production units, electric vehicle charging, etc.; 2026 – 2028.
- High Priority Communities: Disadvantaged communities, low-income communities, Environmental Justice communities, fire-prone communities; 2027 onward.

CHAPTER 1: Introduction

Need for Energy Storage and Emerging Role of Hydrogen

California urgently needs an economic long-duration energy storage (LDES) solution for its excess renewable electricity. Senate Bill (SB) 1369 mandates the need for Green Electrolytic Hydrogen (e-H_2) to store excess renewable electricity from solar, wind, or biomass.[1] The SB 100 Joint Agency Report indicates that California will need a total of 50 gigawatts (GW) or more of energy storage, including 4 GW of LDES, in order to meet its 2045 goal of reliably supplying end-use customers with electric retail sales that are 100 percent renewable and carbon-free.[2] The California Public Utilities Commission (CPUC) has called for 15 GW of new storage and demand response resources by 2030.[3] The California Energy Commission (CEC) is making investments in advanced microgrids and energy storage projects. Conventional batteries, while good for rapid response, become prohibitively expensive for long durations (greater than 8 hours). Highly variable duty cycles are demanded by the customer side of the meter applications at commercial, residential, industrial, and defense facilities. Military mission-critical facilities are mandated for at least 14 days of grid independent operation. A cost-effective solution is needed to meet broad applications of long-duration energy storage and help California meet its clean energy goals.

California Independent System Operator (California ISO) strategy for managing the grid imbalance issues is becoming more critical every year as the market share of renewables is growing. California ISO is exploring several promising concepts and technologies to minimize oversupply and curtailment, as shown in **Table 1**.

[1] https://sd09.senate.ca.gov/news/20180831-california-legislature-passes-skinners-sb-1369-laying-groundwork-green-hydrogen

[2] https://www.energy.ca.gov/publications/2021/2021-sb-100-joint-agency-report-achieving-100-percent-clean-electricity

[3] California Public Utilities Commission – CPUC Integrated Resource Planning (IRP) Scoping Plan Workshop, June 2021.

Table 1. California ISO Strategy for Energy Oversupply, Curtailment, and Shortage

Storage – increase the effective participation by energy storage resources.	**Western Energy Imbalance Market** – expand the Western Energy Imbalance Market.
Demand response – enhance DR initiatives to enable adjustments in consumer demand, both up and down, when warranted by grid conditions.	**Regional coordination** – offers more diversified set of clean energy resources through a cost effective and reliable regional market.
Time-of-use rates – implement time-of-use rates that match consumption with efficient use of clean energy supplies.	**Electric vehicles** – incorporate electric vehicle charging systems that are responsive to changing grid conditions.
Minimum generation – explore policies to reduce minimum operating levels for existing generators, thus making room for more renewable production.	**Flexible resources** – invest in modern, fast-responding resources that can follow sudden increases and decreases in demand.

Energy Storage, Demand Response, and Flexible Resources are needed.

Source: California ISO[4]

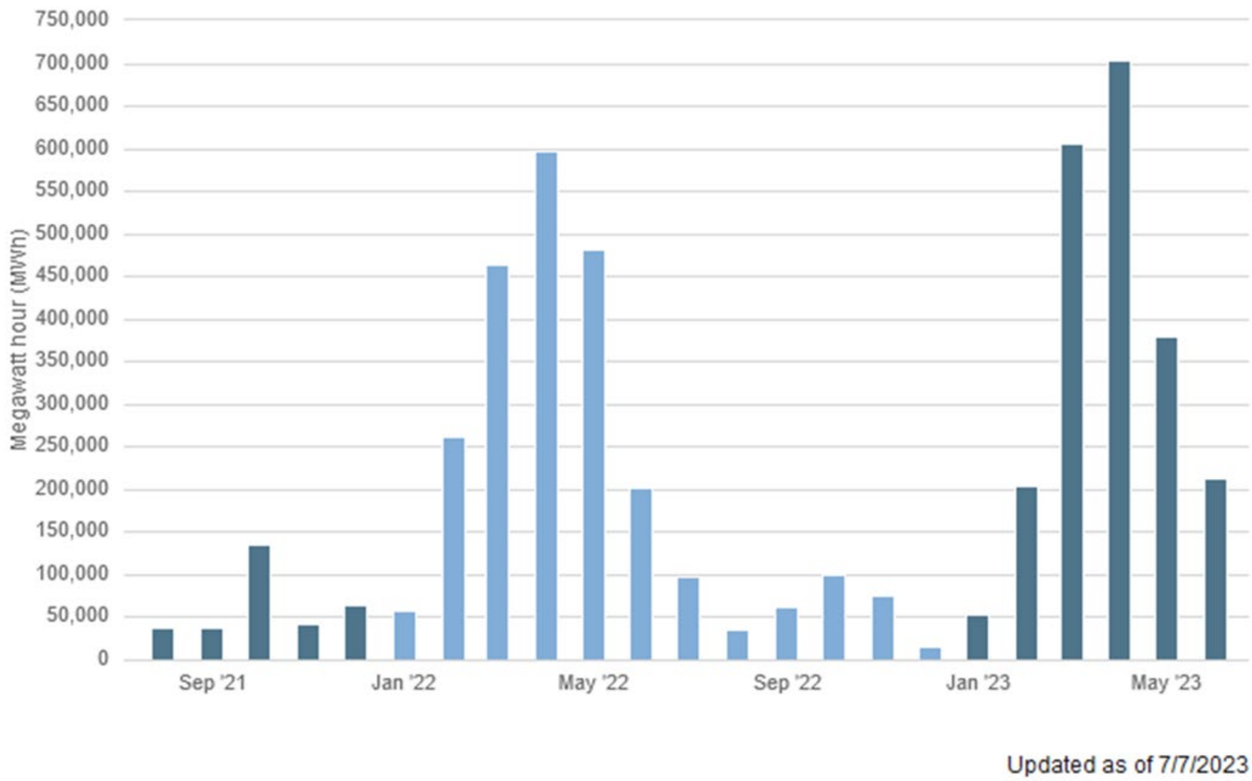
Curtailment is Expensive

It is essential for California to shift to a clean, efficient, and modern grid for both the economy and the environment. This transition to a low-carbon grid provides challenges and opportunities as the state incorporates increasing amounts of renewable energy into the electric system. California's growing portfolio of renewable resources can generate more electricity than is needed, and during these periods of surplus energy, the California ISO's market automatically reduces energy production from renewable resources or "curtails" generation. In rare instances, when economic bids from generators are insufficient, California ISO operators manually curtail production to maintain the balance between supply and demand. While curtailment is an acceptable operational tool, there is an oversupply of electricity at certain times of day with the increasing amounts of renewable resources being installed. The California ISO is seeking solutions to avoid or reduce the amount of curtailment of renewable power to maximize the use of clean energy sources.

Investor-owned Utilities (IOUs) experience significant costs related to the need for curtailment driven by intermittent renewable generation, primarily wind and solar. In **Figure 1** below, California ISO provides monthly curtailment data showing that curtailment during some months exceeded an astounding 700 gigawatt hours (GWh). At 20 cents/kilowatt hour (kWh) this equates to $140 million/month in lost economic opportunity. Cost-effective LDES is needed to support the transition to a zero-emission economy.

[4] https://www.caiso.com/informed/Pages/ManagingOversupply.aspx

Figure 1. California Wind and Solar Curtailments



Monthly curtailment has grown from less than 50 GWh to 700 GWh in 2 years.

Source: California ISO[5]

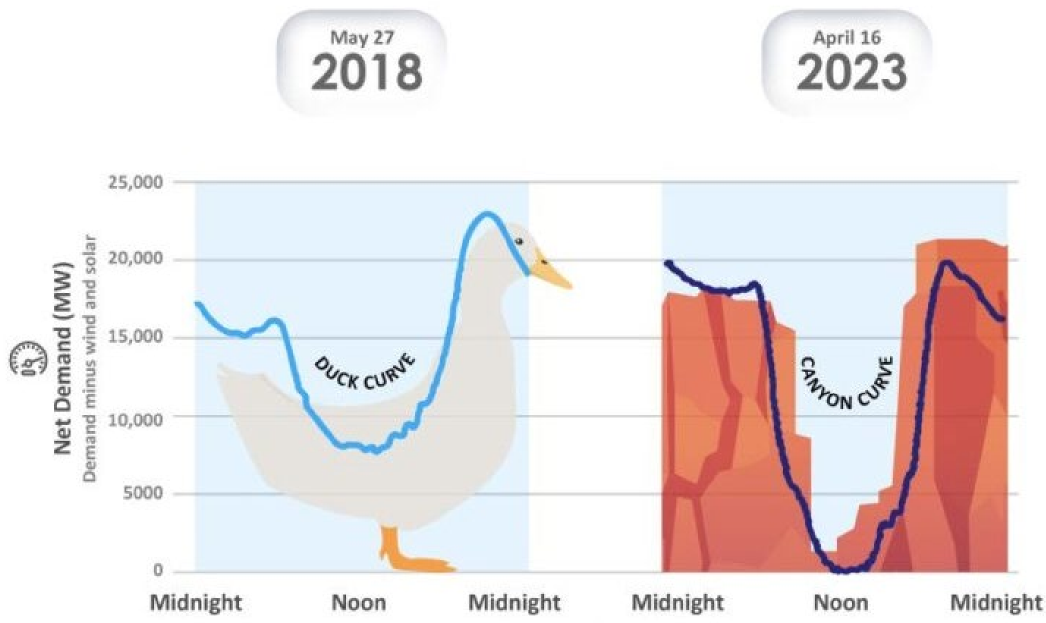
Energy Storage Needed for Balancing the Renewable Grid

Green electricity from renewable sources, primarily wind and solar, is abundantly available in California. In fact, due to their abundance and intermittent nature, a major issue facing IOUs is the cyclical excess to shortage of renewable energy requiring curtailment and other corrective measures; see **Figure 2**. The Advanced Electrolyzer System (AES) is the ideal solution for minimizing the impact and maximizing the capacity factor of renewable energy sources due to the daily cycles of excess to shortage:

- Average daytime excess: 300 to 2,000 megawatts (MW)/day (estimated from curtailment: 100 to 700 GWh/month).
- Shortage in the evening: 5 to 20 GW; Duration: 4 hours; 20 to 80 GWh.

[5] https://www.caiso.com/informed/Pages/ManagingOversupply.aspx

Figure 2. Duck to Canyon Curve → Oversupply Leads to Curtailment



Short supply in evenings needs energy storage.

Source: Electric Power Research Institute (EPRI)[6]

Impact of EV Charging

California is experiencing the highest penetration of zero-emission vehicles in the US. About half of these vehicles are likely to charge in the evening time when there is a significant shortage of electricity. For example:

- Assuming 20 million electric vehicles (EVs) in California and charging at 10 kWh/day per EV results in 200 GWh/day of load representing a huge need for energy storage to help manage the charge events.
- Load shifting for EV charging in the evening means that there is a need energy storage for excess solar during the day.
- The cost of EV charging in the evening has increased from an average of 10 cents/kWh to over 50 cents/kWh due to the short supply of renewable power at that time.
- The levelized cost of storage (LCOS) of 10 cents/kWh using hydrogen (H_2) energy storage makes EV charging in the evening affordable.

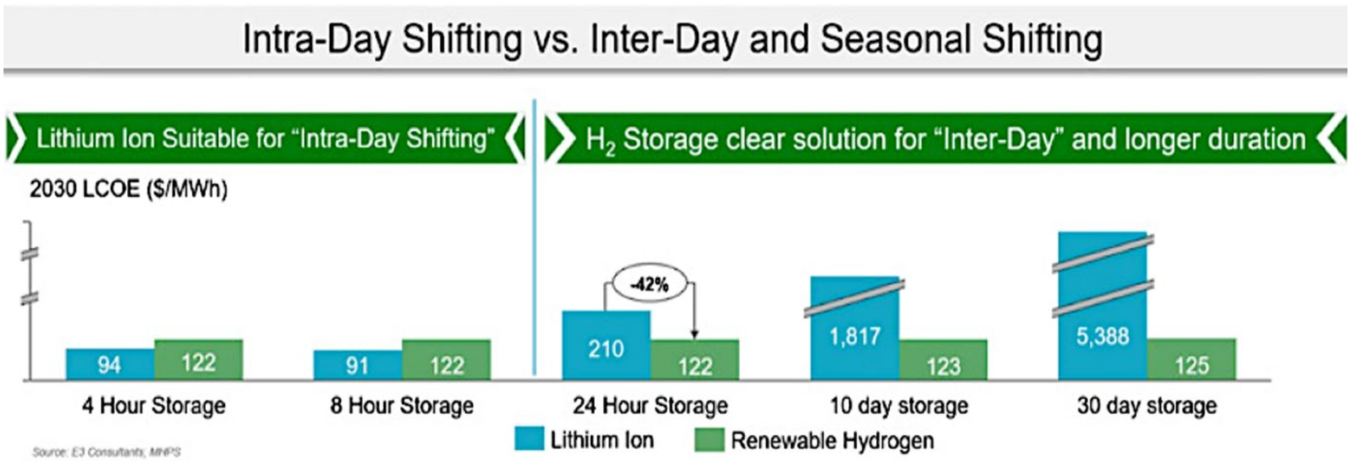
Energy Storage — Battery vs. Hydrogen

Lithium-ion batteries are suitable for short-duration energy storage but become prohibitively expensive for LDES; see **Figure 3**. For short-duration battery storage (i.e., less than eight hours), the levelized cost of energy (LCOE) is estimated at $90-$100/MWh. For 24 hours of storage, the LCOE doubles to more than $200/MWh. For longer durations of 30 days, the battery LCOE increases to an astounding $5,000/MWh, prohibitively expensive storage for

[6] https://www.powermag.com/epri-head-duck-curve-now-looks-like-a-canyon/

California grid support needs. This is due to the linear increase in battery capital costs versus storage capacity and duration. For Tesla Megapacks, 24 MWh of battery storage costs over $11 million.[7]

Figure 3. Competitive Landscape for Energy Storage - Battery vs. Conventional H_2 Battery for short duration, H_2 for long duration energy storage



Source: Energy and Environmental Economics, Inc. Consultants. H_2 from Water Electrolysis vs. Battery[8]

The LCOE for conventional H_2 using water electrolysis is estimated by Energy and Environmental Economics, Inc. Consultants to be $125/MWh. The technoeconomic analyses for AES predict an LCOE of $50/MWh. The 700 GWh/month of curtailed electricity could be used to produce 70,000 tons of AES-H_2, which, at $5,000/ton, has a value of $350 million. An additional advantage of AES technology is its low energy consumption versus H_2 produced from water electrolyzers and pressure swing absorbers.

AES Technology Overview

The T2M team has developed and validated a complete Green Electrolytic Hydrogen Energy Storage System with ultra-high electrical efficiency at competitive costs for customer side of the meter applications. AES doubles the round-trip electrical efficiency of conventional water electrolyzer systems (from less than 40 percent to greater than 80 percent) while reducing their capital cost by about 50 percent. These ambitious goals were reached by eliminating prohibitively high electrical losses associated with co-production of oxygen, and smart process intensification. The overall goal of the project is to develop a commercial AES-H_2 LDES with electricity-in and electricity-out (**Figure 4**) for enhanced resiliency of microgrids and the associated benefits to California stakeholders. Its enhanced safety features make it especially suitable for disadvantaged communities in California to create value from wasted resources.

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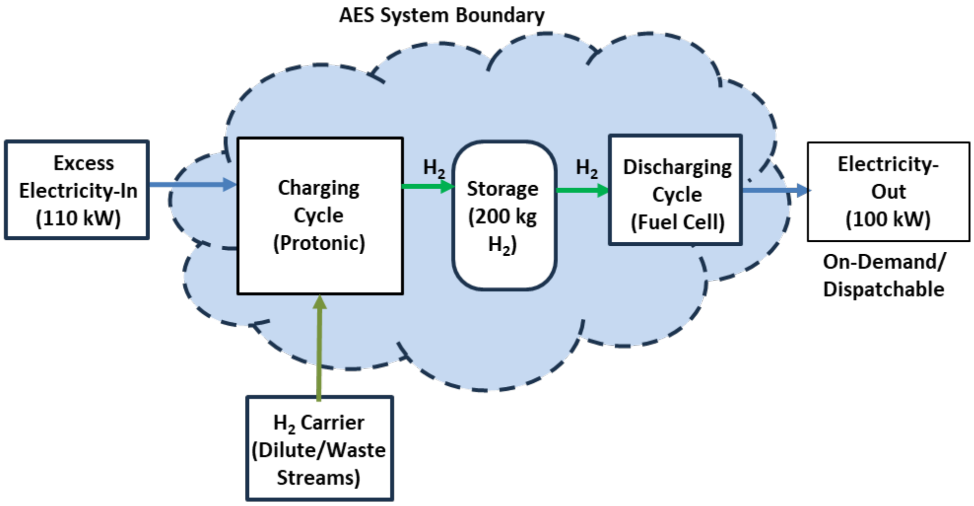
[7] https://www.tesla.com/megapack/design

[8] https://www.ethree.com/publication/

Figure 4. Electrochemical Energy Storage System – Highly Modular and Scalable



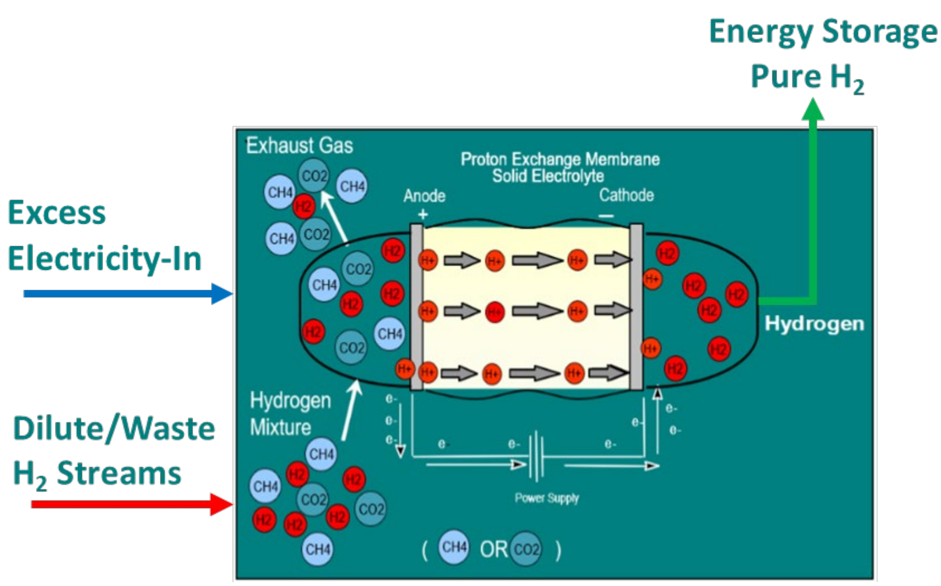
Highly efficient protonic cycle promises a clear pathway for 5 cents/kWh LCOS.

Source: T2M Global

Charging Cycle

The operating principle of the Advanced Electrolyzer cell is illustrated in Figure 5. It has no oxygen (O_2) electrode — just H_2/H_2 electrodes. A very dilute/waste H_2 stream is fed at the anode electrode. Electricity-in is used to selectively produce protons from the dilute/waste stream, and to transfer them through a proton-conducting membrane. At the counter electrode the protons are converted back to pure H_2. The flow of H_2 at the counter electrode can be increased by using a back-pressure regulator set at the desired pressure.

Figure 5. AES Operating Principle for Low Cost $H_2H_2/H^+/H_2$



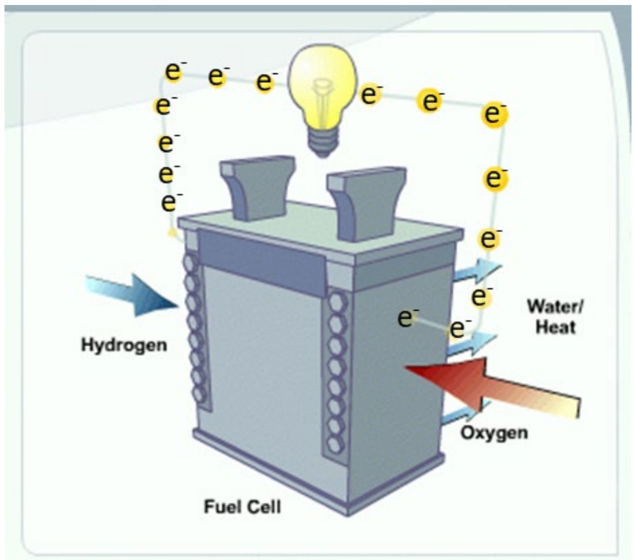
AES Operating Principle for Low Cost $H_2H_2/H^+/H_2$ is the most efficient electrochemical system: 5 to 15 kWh/kg of H_2.

Source: T2M Global

Discharge Cycle

The operating principle of a fuel cell is illustrated in **Figure 6**. It has an O_2 cathode and an H_2 anode. The pure H_2 stream is fed at the anode electrode where the H_2 is split into two protons and electrons. The protons transfer through a proton-conducting membrane electrode assembly to the counter electrode while the electrons flow through an external circuit to the cathode, producing power. At the cathode, the protons combine with O_2 from the air and electrons to generate pure water, heat, and electricity. The amount of power produced is a direct function of the H_2 flowrate at the anode.

Figure 6. Operating Principle Behind a Hydrogen Fuel Cell



Stored H_2 reacts with oxygen in the air → Clean electricity, heat, and water.

Source: T2M Global

Project Goals

The overall project goals and objectives were to develop green electrolytic H_2 for LDES. All major goals have been successfully accomplished. Specific goals and objectives include:

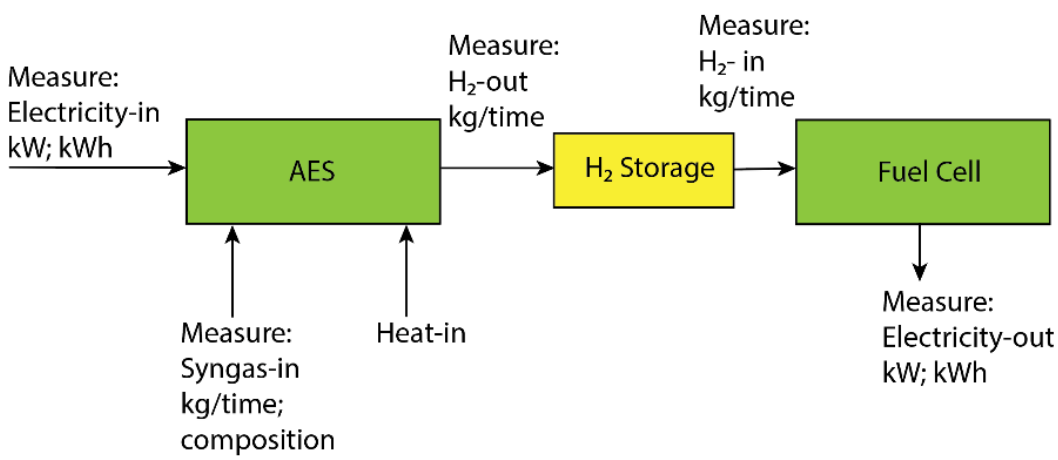
- Develop and validate the AES energy storage system technology for electricity-in/ electricity-out applications. Advanced Electrolyzer Target: one to five kilograms (kg) of H_2/day energy storage, kW-class test vehicle with round-trip efficiency of more than 80 percent.
- Demonstrate feedstock flexibility by operating on different dilute/waste H_2 streams available in California. Synthesis gas (syngas) containing 10 to 20 percent H_2.
- Identify dilute/waste H_2 market opportunities in California for energy storage.
- Improve AES for expanded markets: Streams containing carbon monoxide (CO) up to 10 percent.
- Validate benefits of pressurized operation to reduce operating costs.

- Scale up AES technology to five kg/day to advance technical readiness level from four to six.
- Develop designs for a 100 kW, 100 kg/day H_2 storage building block to enhance grid stability at competitive cost for IOUs and ratepayers.
- Establish readiness for scale-up and prototype development for microgrid deployment.
- Direct current (DC) Microgrid for higher efficiency and lower cost: Eliminate inverter-rectifier for reduction in capital expenditures (CapEx) and operating expenses (OpEx).
- Develop AES deployment strategy in Disadvantaged Communities using guidance from the technical advisory committee (TAC) and IOUs.

Metrics Measured

The high-level measurement points of the measurement and verification (M&V) plan used to validate AES performance are shown in **Figure 7**. While there was a substantial amount of additional process information collected, these are the key measurement points used to verify the performance metrics outlined in **Table 2**.

Figure 7. High-Level M&V Plan



Energy consumption goal less than 15 kWh/kg of H_2 produced.

Source: T2M Global

Table 2. M&V Performance Metrics for Technology Validation

Performance Metric	Performance Benchmark Target	Performance Minimum Target	Performance Goal Target	Evaluation Method	Significance and Accomplishment
Specific Energy Consumption (kWh/kg)	50 to 70	15	10	Controlled experiment with data analytics	Critical to reduce H_2 production cost to less than $4/kg for LDES. Accomplishment: Met stretch goal of 10 kWh/kg

Performance Metric	Performance Benchmark Target	Performance Minimum Target	Performance Goal Target	Evaluation Method	Significance and Accomplishment
H_2 Production Rate for Energy Storage milliampere per square centimeter (mA)/cm^2)	N/A	300	400	Controlled experiment with data analytics	Higher H_2 rate reduces capital cost and ability to meet customer demand. Accomplishment: Met stretch goal of 400 mA/cm^2
Round-trip electrical efficiency (%)	25 to 36	60	80	Controlled experiment with data analytics	A high round-trip efficiency is necessary for LDES and complement battery storage for short durations. Accomplishment: Exceeded stretch goal of 80%
H_2 Recovery from Dilute Streams (%)	NA	70	80	Current measure-ment (ampere)	A higher H_2 recovery translates to lower capital cost and reduces cost of H_2 production. Accomplishment: Met stretch goal of 80%
Feedstock Flexibility (%H_2)	NA	20	10	Electro-chemical testing	Expand addressable market for energy storage. Overall market size increases tremendously with the ability to electrolyze dilute/waste H_2 streams of varying compositions. Accomplishment: Met stretch goal of 10% H_2

Successful accomplishment of these metrics validated benefits of H_2 energy storage, including meeting or exceeding stretch or reach goals.

Source: T2M Global

Benefits to Ratepayers

In the near term, a H_2 LDES system is uniquely suitable for the customer side of the meter applications, whether it is for residential or industrial customers to reduce cost of electricity for their operations. This is especially valuable for California customers that are experiencing grid stability issues likely due to daytime excess production of solar photovoltaic (PV) and pockets of capacity shortages due to the closures of fossil and nuclear plants. The AES Module can use dilute/waste H_2 streams without any adverse environmental emissions. This lower cost electricity storage solution promises lower electricity rates and supports the intermittency of renewables for greater penetration. It offers significant benefits to California stakeholders summarized as:

- Highly Versatile LDES System: Rapid removal of excess electricity for microgrid safety, on-demand dispatchable power during shortages.
- Ultra-high Electrical Efficiency with Enhanced Safety and Lower Cost: Greater than 80 percent using oxygen-free electrolysis with reduced fire hazard.
- Feedstock Flexibility for Greater Deployment in Disadvantaged Communities: Makes energy storage readily available to the low-income communities, disadvantaged communities, and environmental justice (EJ) communities for health and economic benefits.
- Lower Cost DC-Microgrids: Eliminates round-trip losses in alternating current/direct current (AC/DC) conversion and cost.
- Modular Design for Lower CapEx: Design for manufacturing, ultra-compact footprint for rapid and low-cost deployment, solid-state device for easier maintenance.
- Enhanced Safety for Disadvantaged Communities: Win-win solution to forestry waste for fire prevention and production of biogas – a source of H_2 energy storage.
- Rapid Response LDES: Waste heat recovery and reuse for lower CapEx and OpEx. Potential to offer 5 cents/kWh LCOS.
- Water Independent System: Potential to export co-product, high-purity water for drought-prone California, especially low-income communities, disadvantaged communities, and EJ communities.
- Integrated Device for Lower Cost: Electrolysis + H_2 storage in the same enclosure eliminates the separate higher cost compressed H_2 storage and safety equipment.

CHAPTER 2: Project Approach

Project Team and Stakeholders

The H_2 LDES project was managed by T2M Global as the prime recipient. Mr. Pinakin Patel, President and Chief Executive Officer of T2M Global, was the Project Director and provided high-level project direction. He was supported by Dr. Ludwig Lipp, Vice President of T2M Global, for technology development and by Mr. Niraj Patel, Chief Financial Officer of T2M Global, for financial modeling and reporting. The project management efforts included reporting, outreach to stakeholders, and coordinating the efforts of T2M's staff, subcontractors, advisors, and vendors. Among the IOUs, representatives from Pacific Gas and Electric (PG&E) and Southern California Gas provided guidance for H_2 LDES development and deployment opportunities.

The California team included subcontractors, who were instrumental in developing key components of the AES stack and balance of plant (BOP) components of the H_2 LDES. This included a supply chain partner in feedstock flexible AES cell hardware with extensive experience in technology scale-up, validation testing, and improvements. T2M has previously partnered with them to develop novel applications of different H_2 carriers and their applications in energy storage and production. Another supply chain partner has more than 100 years of experience in biogas upgrading equipment, pressure vessels, design, and fabrication of modular systems for fuel cells and electrolyzers. They ensured design, fabrication, and delivery of key components for AES testing.

The TAC included major stakeholders in H_2 energy storage systems. The TAC consisted of experts from eight different stakeholder entities that provided highly valuable strategic guidance and input for market-responsive product development. T2M team members have received special recognition awards from the Department of Energy (DOE) and the Department of Defense (DOD) for successfully developing advanced H_2 and fuel cell technologies. This experience has helped T2M in AES scale-up, validation, and integrated building block design for H_2 LDES deployment.

Technology Options: Water Electrolyzer vs. Syngas Electrolyzer

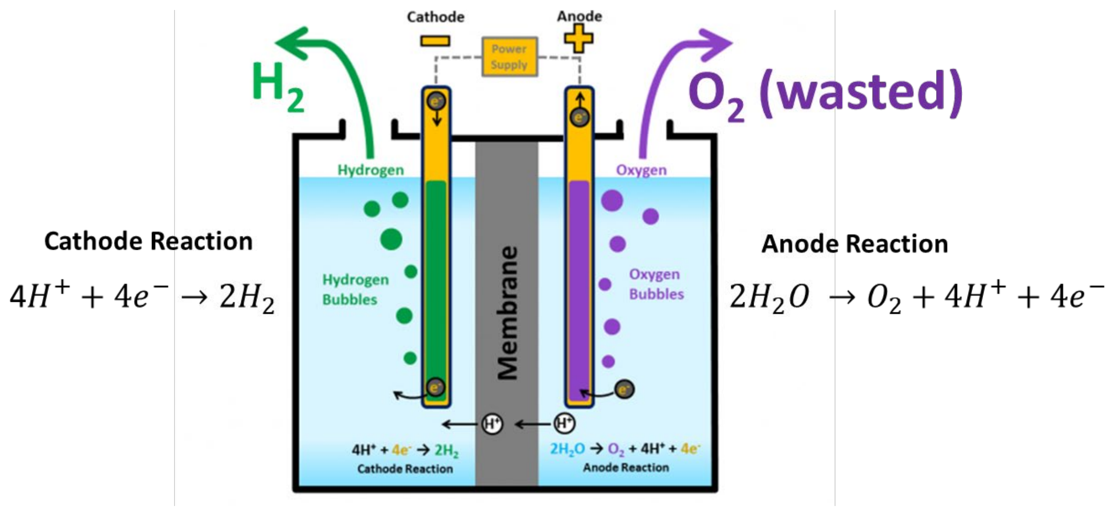
Water Electrolysis

The current method to produce H_2 using excess electricity. Its popularity is growing worldwide because of the transition to a zero-emission economy. Figure 8 shows the water electrolysis process and the associated electrochemical reaction. It involves using DC electric current to split water (H_2O) into its constituents, H_2 and O_2, at two separate electrodes. This conventional H_2 production technology suffers from several challenges that make it unattractive for LDES:

- Water electrolyzer is energy intensive: More than 50 MWh/ton of H_2.
- High OpEx: At 10 cents/kWh, this translates to OpEx of $5000/ton of H_2.

- High CapEx: up to \$3 million/MW, making it economically challenging for LDES.
- Resource-constrained technology: It requires substantial amounts of highly purified water; up to 20 tons of water per ton of H_2—a scarce resource in drought-prone California.
- Stranded resource: Coproduct O_2 is virtually wasted, **Figure 8**.
- Inferior compatibility with intermittent renewables: Difficult to load follow without sacrificing performance and durability.
- Difficult to permit due to safety concerns: For every ton of H_2 produced, eight tons of oxygen are produced, imposing safety challenges. The large volumes of pressurized H_2 and O_2 co-products in presence of electricity (and platinum catalyst) pose a risk for fires and explosions. This is a permitting and safety issue, especially for deployment in disadvantaged communities, which have traditionally suffered from such safety, health, and fire hazards.

Figure 8. Conventional Technology for Electrolytic H_2 Production



Water electrolysis is the most popular and well-proven method but is an expensive and energy-intensive process.

Source: Office of Energy Efficiency & Renewable Energy[9]

Alternate H_2 Carriers

The high electrical consumption in water electrolyzers above is mainly due to the co-production of O_2. About 80 percent of the energy input to split water is used to make O_2, which is a wasted resource. Alternate H_2 carriers that are O_2-free provide an important opportunity to reduce H_2 LDES costs to competitive levels (less than 5 cents/kWh LCOS). In addition, the O_2-free H_2 carriers offer greater safety and easier permitting. Oxygen-free H_2 carriers include:

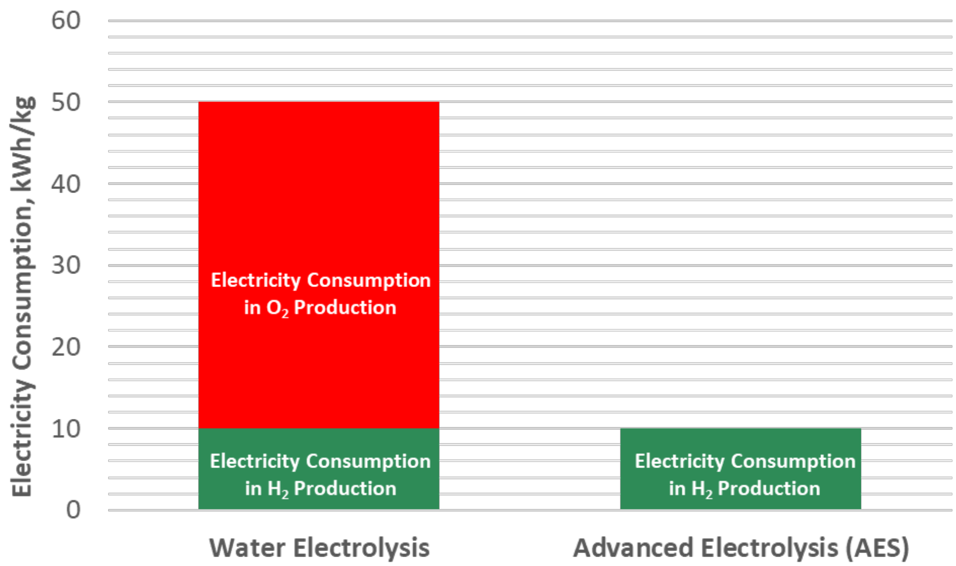
- Ammonia – NH_3.
- Methane – CH_4.

[9] https://www.energy.gov/eere/fuelcells/hydrogen-production-electrolysis

- Syngas – H_2 + CO + CO_2.
- Tail gases from industrial processes such as Steam Methane Reforming (SMR), pyrolysis, semiconductor, steel manufacturing, fuel cell exhaust, etc.
- Biogas, Anaerobic Digester Gas.

Electrolysis of O_2-free carriers promises over 80 percent reduction in electricity used, **Figure 9**. This leads to significantly higher round-trip efficiency.

Figure 9. Competitive Landscape for Green Hydrogen Production



AES uses 80 percent less electricity than water electrolyzers.

Source: T2M Global

AES technology eliminates this problem; it is O_2-free. All safety hazards are significantly reduced, making AES superior for beneficial deployment in disadvantaged communities, as well as other market segments. **Table 3** shows a comparison of important performance metrics between AES vs. battery and conventional water electrolysis systems. A hybrid system incorporating AES-H_2 storage for long duration, with battery storage for rapid response needed for grid intermittency, can provide a complete energy storage solution that addresses all cases considered.

Table 3. Competitive Landscape for Energy Storage Technologies

Comparable Attributes	Current	Water Electrolysis	Advanced Electrolysis (AES)	Advanced Electrolysis (AES)
Storage Technology	**Battery**	**Water**	**Baseline**	**Improved**
Overall Round-trip Efficiency	81%	30%	84%	96%
Electricity Use, kWh/kg H_2	N/A	>50	15	10
Installed Cost ($/kW)	$1,500	$3,000	~$1,000	$800

Comparable Attributes	Current	Water Electrolysis	Advanced Electrolysis (AES)	Advanced Electrolysis (AES)
Self-Discharge (%/month)	2 to 5%	0.2%	0.1%	0.1%
System Life, years	10	5	15	20

AES technology offers higher efficiency at lower cost.

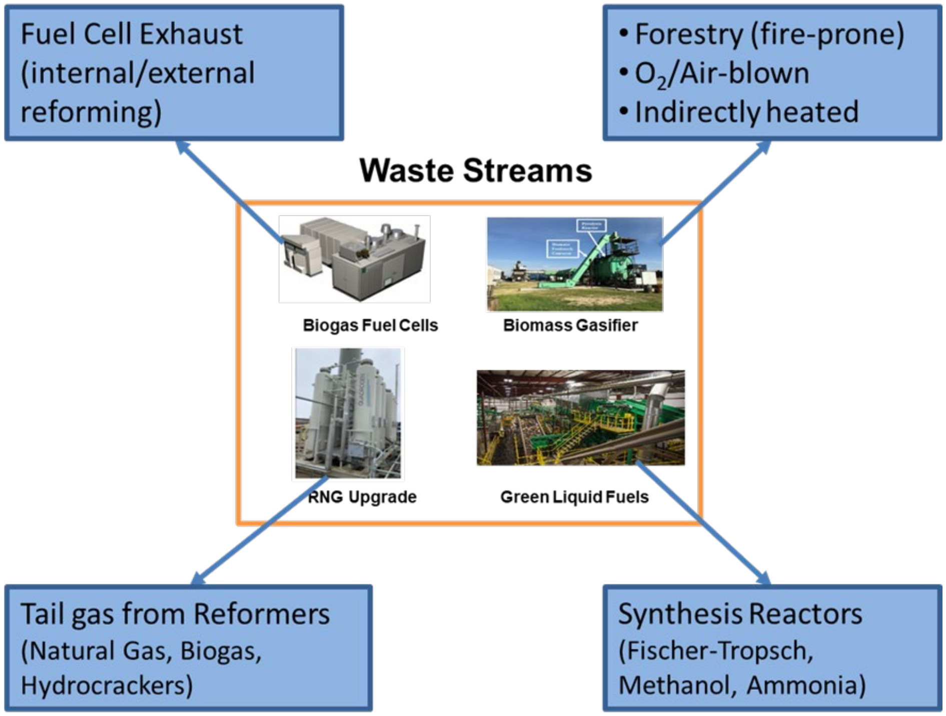
Source: T2M Global

Sources of Dilute/Waste H_2 Streams (Charging Mode)

AES does not use high purity water – a precious resource. Instead, it uses dilute/waste streams of H_2. California is the largest producer of H_2 in the country. Therefore, it is also the largest source of waste/dilute streams of hydrogen. The demand for hydrogen is growing in response to the green mandates in California. This demand will further increase the waste/ dilute streams as a feedstock for green hydrogen, for example, tail gases from fuel cells, biomass gasification, liquid biofuels, biogas-fueled reformers, and green refineries, as illustrated in **Figure 10**. The wide range of feedstocks available for green H_2 production from diverse industries are shown in **Figure 11**. These resources typically are wasted and go to landfills or are flared/vented. This is a lost economic opportunity worth multi-billion dollars. AES technology upgrades these wasted resources to higher value H_2 using excess renewable electricity.

Estimates of potential waste/green H_2 sources are presented in **Table 4**. Near-term opportunities include fuel cell power plants operating on biogas/renewable natural gas (RNG). For every 100 MW of fuel cell power, typically about 25 MW of dilute H_2 stream is underutilized. It is burnt to produce heat, which is largely wasted. Both the CEC and the California Air Resources Board (CARB) are funding more than $500 million to produce green liquid fuels or biogas/RNG from waste biomass (to eliminate sources of severe pollution, especially in disadvantaged communities). Successful deployment of these technologies will dramatically increase availability of the waste/green H_2 streams for LDES applications. Preliminary estimates shown in **Table 4** for waste/green H_2 streams show a gross potential of energy storage worth 200,000 GWh/year. This is enough energy storage to convert the current expensive curtailment and provide dispatchable power on demand during shortages in the evening, as well as long duration storage needs. At 10 percent addressable market share for AES, 20,000 GWh of green H_2 can be produced in the near term. This is a very promising opportunity to firm up CEC investments for resilient microgrids, especially on the customer side of the meter applications.

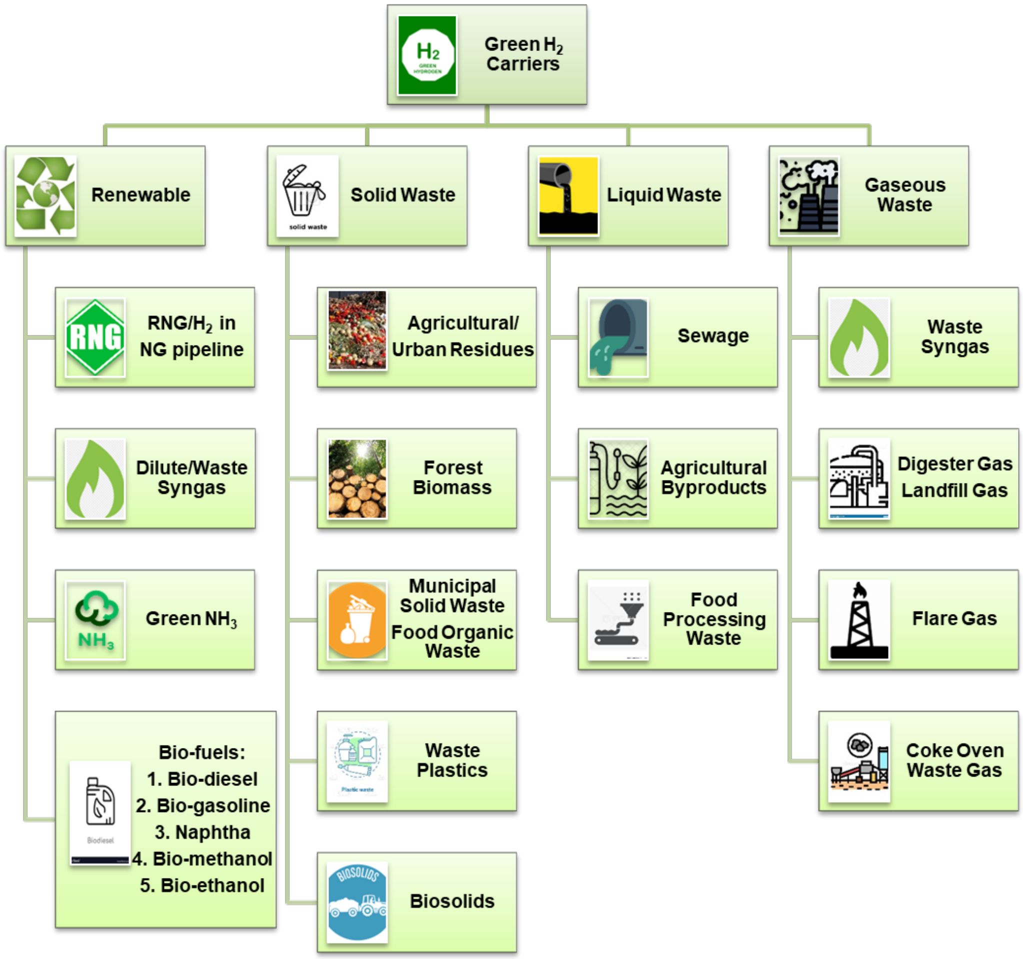
Figure 10. Feedstocks for Green H_2 Energy Storage



California produces over two million tons/year of H_2 → Abundant waste H_2 streams.

Source: T2M Global

Figure 11. Feedstocks for Green Electrolytic H_2



Significant sources of O_2-free carriers for AES across multiple industries

Source: T2M Global

Table 4. Abundance of Waste H_2 Streams for Energy Storage in California

Potential Customers (Disadvantaged Communities)	Waste/Green H_2 Sources	Electricity Storage, GWh	
		Gross	Addressable
Electric Utilities - (Wood yards)	Woody Biomass (Gasifiers, Digesters)	30,000	3,000
Gas Utilities (RNG, LFG), Green H2	PSA Tail Gas	25,000	2,000
Municipal Wastewater - (Biogas)	Tail Gas Fuel Cells, SMR (>100 sites)	40,000	5,000
Food Processors	Digester Tail Gas	35,000	4,000
Agricultural, Forestry	Woody Biomass, ammonia	70,000	6,000
Total	**>100M tons/yr in CA**	**200,000**	**20,000**

Green H_2 from wasted resources can support 20,000 GWh/year of electricity storage.

LFG = landfill gas; PSA = pressure swing adsorption; SMR = steam-methane reforming

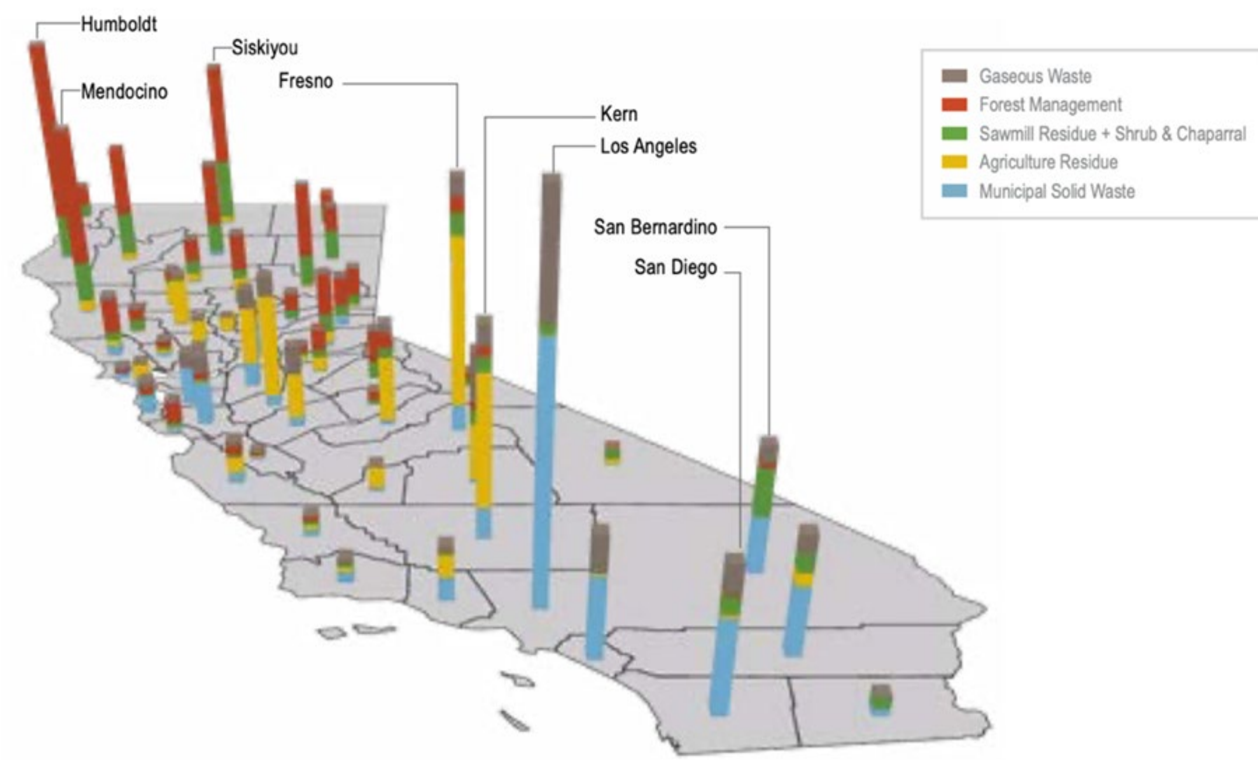
Source: T2M Global

Near-term Opportunity

In recent years, H_2 as a transportation fuel and storage medium for the power sector has experienced a resurgence in interest. There are various ways in which H_2 can be produced, and certain places around the world where it occurs naturally, but these are not widespread. Primary means of H_2 production include steam reforming of natural gas or biogas (methane), splitting water through electrolysis, and various other lower technology readiness possibilities, such as, solar-thermochemical, photo-electrochemical, and bio-based solutions, for instance, production through certain types of algal processes.

While much attention is being paid to the electrolysis pathways because of their inherently low carbon nature, biogas pathways can also offer very low or even negative carbon intensity depending on the feedstock and process for production. In fact, there is a potentially large supply of biomass/biogas feedstocks for low carbon intensity hydrogen production in California. An estimated 56 million dry tons of waste biomass could be available by 2045 in California and could potentially produce up to 5 million tons of hydrogen per year (Baker, et al., 2020). A recent estimate of the state's available biomass resources for biogas and/or hydrogen production (**Figure 12**) identifies feedstock source availability by region. Southern California production resources are dominated by municipal waste and other gaseous waste sources. Central California has a mix of those sources as well as agricultural residues and forest waste. Northern California sources come mostly from wood waste, forest management, and sawmill residues.

Figure 12. Waste Feedstock Availability Estimate for California



Abundant feedstocks from diverse sources make H_2 LDES attractive in the near term.

Source: Baker et al., 2020

The concept of converting municipal solid waste, agricultural waste, and forest waste to syngas has been pursued for many years, especially in Europe. Furthermore, converting the syngas to relatively (or very) pure hydrogen is a newer concept. A key issue is that syngas contains relatively high levels of CO, on the order of 30 to 40 percent, along with similar levels of hydrogen depending on the process and feedstock. T2M Global's H_2 Booster technology can produce additional H_2 from this CO using water-gas-shift. The most established method for producing pure hydrogen from these mixed syngas streams is pressure-swing adsorption (PSA). PSA is fully commercial technology, but it is somewhat cumbersome to implement for pure hydrogen production as it effectively involves removing all other gas species in a syngas stream through the use of adsorbents under pressure, leaving relatively pure hydrogen in the gas stream.

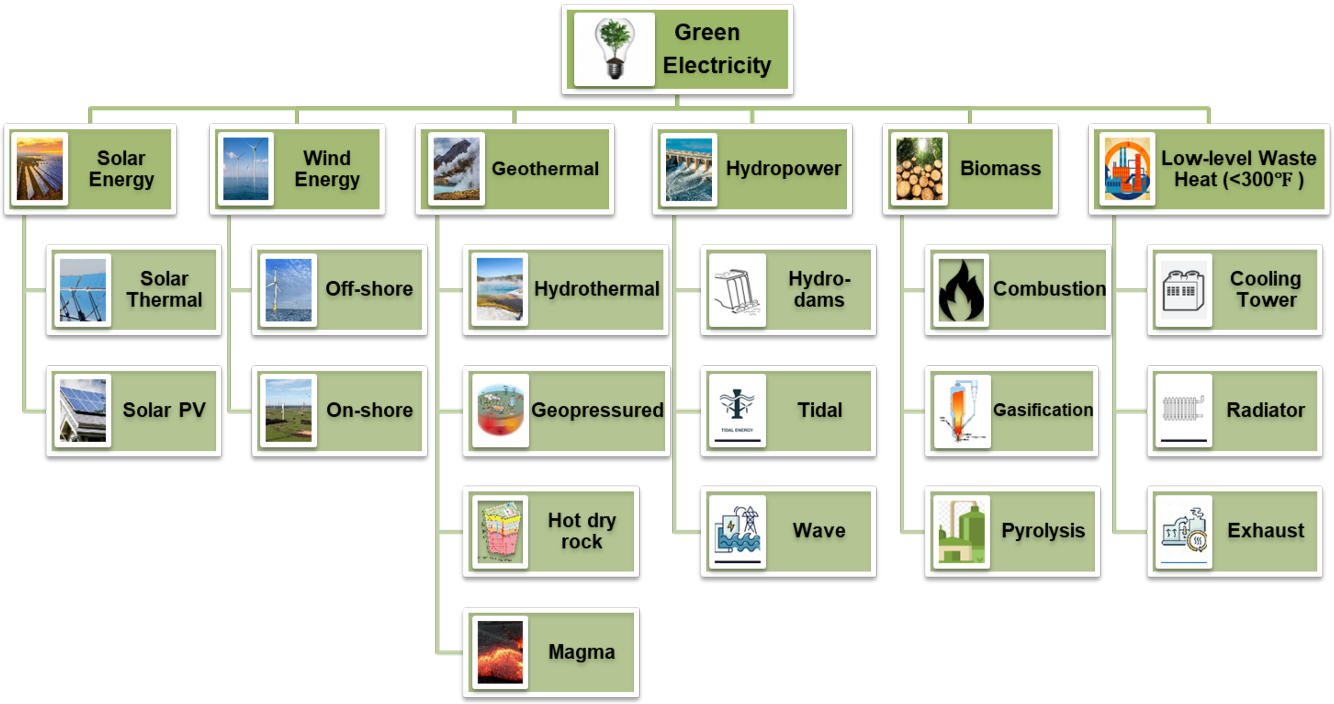
Over a dozen technology companies in California were short-listed as a source of dilute/waste H_2 streams from their biogas production facilities, existing or planned. These companies mainly focus on gasification-based technologies. Recent interest in low-carbon fuels has triggered other potential technologies in pyrolysis and plasma-based conversion systems. The companies that have significant biogas projects in the California market include All Power Labs, Raven SR, Sierra Energy, and West Biofuels. All Power Labs is currently working with PG&E on a waste-to-electricity project in Mendocino, California where an 80-kW combustion engine generator is being operated to produce electrical power that is being exported to the grid. Raven SR is constructing a municipal solid waste-to-hydrogen project in Richmond, California that will produce up to 5,500 kg of purified hydrogen per day from syngas from 100 tons per day of municipal solid waste feedstock. Sierra Energy operates a biogas facility at Fort Hunter Liggett in Monterey County that converts food and other waste from the Army base to biogas, with power production, liquid fuels (Fischer-Tropsch process[10]), and H_2 all being considered as uses for the biogas. Finally, West Biofuels in Woodland, California has an operational dual fluidized bed gasifier system.

Sources of Green Electricity

California's rapid expansion of renewable energy sources, primarily wind and solar, has created a severe overabundance of renewable power during the day, resulting in costly and inefficient curtailments of renewables. This represents an ideal source of green electricity for AES-H_2 energy storage, allowing excess intermittent renewable power to generate high-value H_2 rather than being curtailed. **Figure 13** shows the diverse range of green electricity sources available in California. These multiple sources integrated in a hybrid energy storage system using H_2 provide a highly reliable solution for grid resiliency for the transition to a zero-carbon economy.

[10] https://netl.doe.gov/research/carbon-management/energy-systems/gasification/gasifipedia/ftsynthesis#:~:text=The%20Fischer-Tropsch%20process%20is%20a%20catalytic%20chemical%20reaction,H%202%20O%20Where%20n%20is%20an%20integer.

Figure 13. Sources of Green Electricity



Excess electricity + Waste feedstocks + AES → Green H_2 LDES

Source: T2M Global

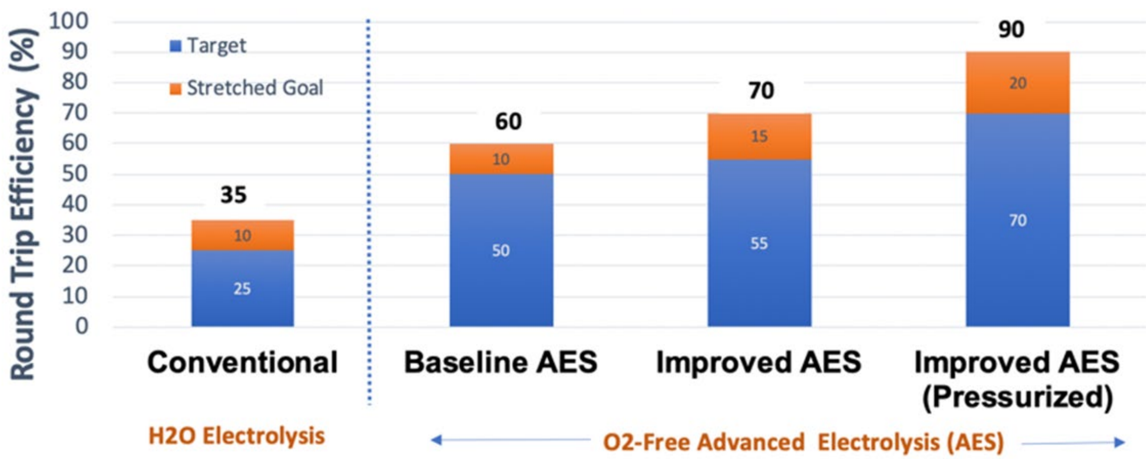
Flexibility to Operate on Different Dilute/Waste H_2 Streams

Dilute H_2 streams may contain carbon dioxide (CO_2), CO, nitrogen (N_2), and low concentrations of H_2. The presence of diluents may influence energy storage efficiency, cycle life, and durability. A survey of available dilute/waste H_2 streams showed the concentration of these diluents varies from a few percentage levels to as much as 60 percent. AES testing was performed under simulated conditions to measure the impact on performance, specifically on the charge cycle to make electrolytic H_2.

Lower-Cost Hydrogen Using Pressurized AES

Performance of both electrolyzers and fuel cells increase significantly with operating pressure, **Figure 14**. There is a potential to double the production capacity and increase operating life at elevated pressures, guiding the design approach. Through an increase in pressure, the operating cost can be reduced; that is, the specific energy consumption of AES, but the initial capital cost increases to make the AES module and the associated electrical balance of plant (E-BOP) and mechanical balance of plant (M-BOP) pressure tolerant.

Figure 14. Strategy to Increase Round-Trip Efficiency for H_2 LDES



Pressurized operation is beneficial → reduces OpEx.

Source: T2M Global

AES Building Block Design (100 kW-class, 100 kg/day H_2 Target)

The AES Commercial Module design focuses on a highly robust hydrogen purification system with competitive CapEx and OpEx. AES capital cost is a direct function of the production capacity of the AES building block (near-term target 100 kg H_2/day). The AES operating cost depends on the operating cell voltage, which determines the overall electrical efficiency of the system. The operating current density, a measure of H_2 flux, determines the capital cost. This requires a complex trade-off between operating current density and cell voltage, as well as limitations in the supply chain to make the larger capacity components with acceptable quality and production cost.

Parametric Analysis for 100-kW Building Block

The team first determined, and then conducted, parametric analysis on the various factors that contribute to increasing H_2 production capacity from a 5 to 10 kg/day level to the 100 kg/day near-term target for the building block (Target: 100 kg/day, 2.4 MWh). The overall objective is AES cell and stack design for a 100 kg/day building block leading to a 1ton/day module design for demonstration and deployment. These parameters include current density (H_2 flux), cell area, number of cells per stack, pressure, and the number of stacks per module for the building block. The scale-up range for these parameters has been identified, along with the potential risk level associated with each parameter. The parametric analysis provides guidance for scale-up activities. In addition, the component supply chain limitations were important considerations in selecting the parameter range for greater capacity of H_2 production. T2M is evaluating the supply chain to expand the cell and stack area to decrease the overall cost of the building block.

AES-H_2 Module Design for MW-class LDES (1 ton/day H_2)

The AES-H_2 building block described above is a platform for a commercial product for MW-class LDES module. The team evaluated configuration options for the one ton/day AES-H_2 module using all-weather and pressurizable enclosures of different sizes. The analysis considered the pros and cons of designs with two, four, and six stacks per enclosure using the current supply chain. In a multi-stack module, the number of manifolding connections and interfaces increases linearly with the number of stacks, that is, H_2 production capacity. These additional connections increase capital costs and potentially maintenance costs. As a result, a plug-and-play design strategy has been identified for rapid installation and easier access for maintenance. **Figure 15** shows an example of a fuel cell installation with a high degree of modularity and maintainability. This installation is in a high traffic entrance area of a shopping mall. The team has elected to benefit from this design strategy for the AES module. **Figure 16** shows the multi-stack design for MW-class H_2 energy storage. It has components for the charging cycle (to convert excess electricity to H_2) and for the discharge cycle (to convert stored H_2 back to electricity in fuel cell mode).

Battery vs. H_2 Energy Storage

The MW-class module will have separate H_2 storage tanks. The size of the H_2 storage, namely, number of cylinders, determines the energy storage capacity. For LDES applications, this is a very attractive design virtue. With a relatively small incremental cost for H_2 cylinders, the LDES energy storage capacity can be increased from days to weeks and months. **Figure 17** shows a conceptual layout for MW-class AES-H_2 energy storage with all major components sized for 50 MWh of storage. It also compares its footprint with 50 MWh of commercial battery packs from Tesla. The sizing and price of battery packs were derived from Tesla's website quotation page. The preliminary estimates for 50-MWh storage show a 50 percent reduction in both the footprint and capital cost by replacing the lithium-ion battery storage with AES-H_2 storage. The highly promising results, presented later in this report, warrant further development and deployment of AES-H_2 technology to achieve Electric Program Investment Charge program goals set by the CPUC.

Figure 15. Modular Plant for Rapid Field Installation

Good example for AES deployment and maintainability.

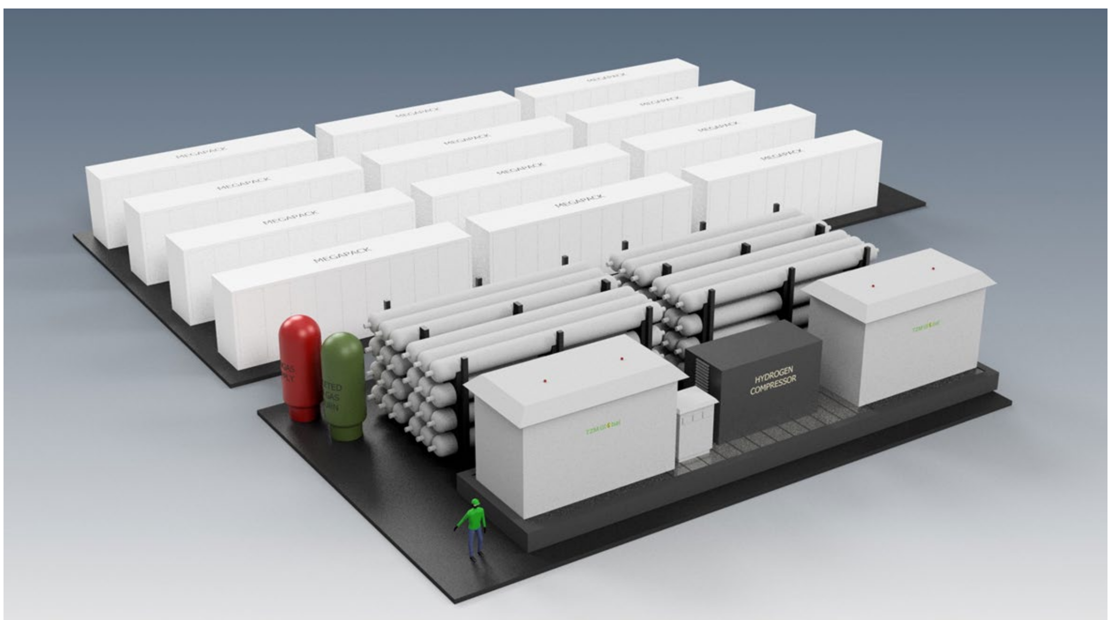
Source: T2M Global

Figure 16. MW-class Module for H_2 LDES - 50 MWh Storage

Modular plug-and-play design for rapid deployment in LDES applications.

Source: T2M Global

Figure 17. Battery vs. AES-H_2 for LDES: MW-class, 50 MWh Storage



H_2 promises 50 percent smaller footprint and 50 percent lower cost.

Source: T2M Global

CHAPTER 3: Results

Sources of Dilute/Waste Hydrogen Streams: Early Adopters

California has an abundance, over 100 million tons per year, of wasted resources containing H_2. More than 40 candidate sites have been identified for H_2 energy storage applications. These dilute/waste hydrogen streams from a variety of industrial operations are summarized below:

- Biomass gasifiers for biogas to produce green electrolytic H_2:
    - Six different types of gasifiers identified and surveyed.
    - High-quality syngas using indirectly heated gasifier in Sacramento area.
    - Medium-quality syngas: Simeken (50 tons/day biomass), Raven, Sierra Energy.
    - Low-medium quality syngas from air-blown gasifiers: APL, KORE, Plasma.
- Biomass digester sites for biogas:
    - More than 20 potential sites identified qualify for RNG incentives.
    - Municipal wastewater – Fountain Valley, Los Angeles Sanitation, San Jose, etc.
    - Industrial wastewater – Tulare, Pacific Coast Producers, Turlock, Sierra Nevada Brewery, etc.
    - Landfill gas – Freemont, Yorba Linda, Los Angeles County, etc.
- RNG and SMR sites: Hydrogen refueling stations, six sites identified and surveyed.
- Biogas fuel cell sites: more than 12 sites identified in disadvantaged communities, low-income communities, and EJ communities.
- Utility woodyards – forestry waste: 8 sites identified, win-win solution to forest fire prevention and green H_2 for EV charging in the evening during shortages in the grid.

AES Technology Validation and Durability Testing

The AES technology was scaled up 50 times, from a 100-watt level to a 5,000-watt level. The technology validation required corresponding scale-up in facility and testing capability to evaluate feedstock flexibility and quantify benefits of pressurized operation. To support the successful development and demonstration of the kW-class AES-H_2 energy storage system, the T2M team scaled up the test facility from single cell/watt level/ambient pressure operation to kW-class/multi-cell/pressurized operation system, as shown in **Figure 18**.

Figure 18. Test Facility Scale-up, Pressurized, and Feedstock Flexible Operation

Validated AES Operation on a variety of dilute/waste H_2 streams: Up to 60 pounds per square inch (psi)

Source: T2M Global

Increase H_2 Production Capacity: Target 5 kg/day H_2

The AES cell, stack, and system hardware were scaled up to 5 to 10 kg/day level. **Figure 19** shows the complete assembly of the AES system in an all-weather enclosure for indoor or outdoor installations. This AES system is capable of simulated dilute/waste H_2 streams to produce high purity H_2. It uses the following sub-systems operating in an integrated mode with emphasis on unattended operation with remote monitoring.

- Mechanical balance of plant: Feedstock supply and heat exchangers.
- Electrical balance of plant: Power supplies, uninterruptible power supply, fuses and breakers.
- Control system: Process instrumentation and Programmable Logic Controller.
- Safety system: Sensors and dedicated certified safety controller, fully automated.
- Cooling system: Liquid coolant, expansion tank, coolant pump, radiator with fan.
- Power conversion system: Reversible AC to DC inverter/rectifier with DC to DC buck/boost power controller with current and voltage regulation.

- Communications and data acquisition: Remote monitoring, data collection, alarms, event recording with internet compatibility.
- Reformer for simulated syngas production.

Figure 19. kW-Class AES System for H_2 LDES Validation

Modular unit provided data for scaleup to 100 kg/day building block.

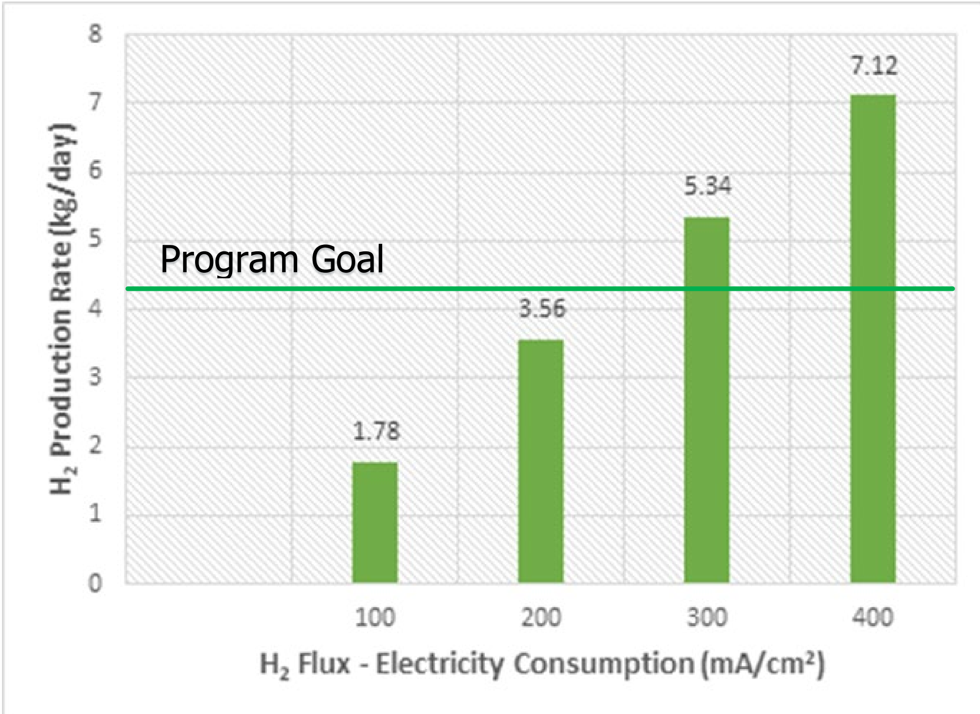
Source: T2M Global

The simulated syngas feedstock for the AES module was generated via steam reforming of methanol, resulting in a composition by mass of:

- H_2 = 10.03 percent
- CO + CO_2 = 73.56 percent
- H_2O (steam) = 16.41 percent

The H_2 production rate versus stack current density for these test runs is shown in **Figure 20** below. A H_2 production rate of 5.6 kg/day was achieved at a stack current density of 318.2 mA/cm^2.The increase in H_2 production capacity was achieved by increasing H_2 flux (current density) from 100 mA/cm^2 level to 300 mA/cm^2 as shown in **Figure 20**. Increasing operating current density from 200 to 400 mA/cm^2 increased the H_2 production capacity from 3.56 to 7.12 kg/day, exceeding the project goal by 40 percent. Increasing current density has the benefit of higher purity H_2 produced, greater than 99.99 percent, as shown in **Figure 21**. A two-times increase in current density (H_2 flux or production rate) will decrease the size of AES stack by 50 percent; thus, leading to 50-percent reduction in associated capital cost. This data was used for 100 kW-class building block design as described later in this report.

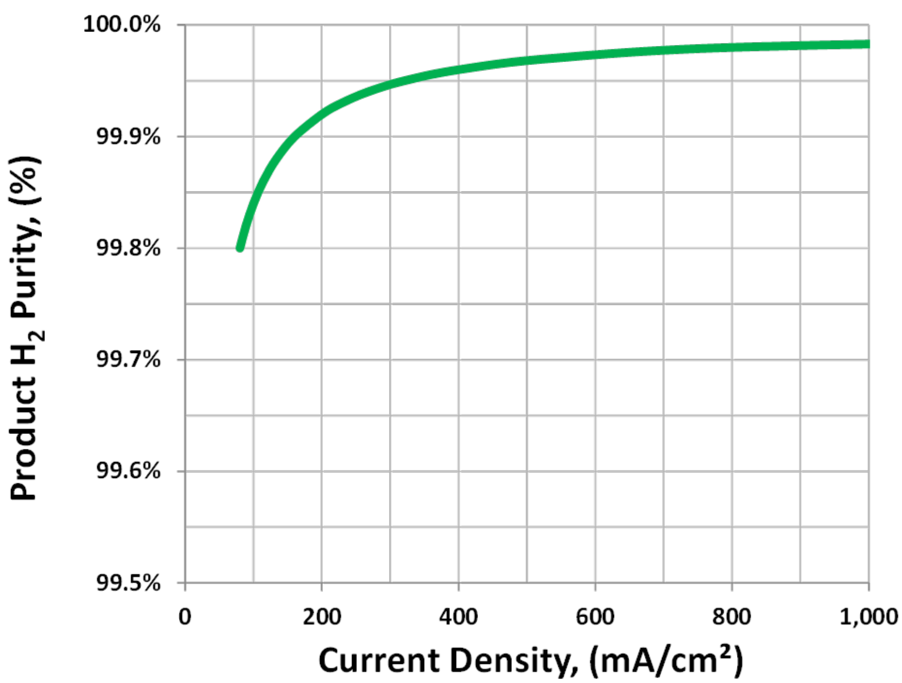
Figure 20. H_2 Production at Different Current Densities



CEC program goal of 5 kg/day was met and exceeded.

Source: T2M Global

Figure 21. H_2 Product Purity vs. Production Rate



H_2 purity improves with increase in H_2 production rate.

Source: T2M Global

Feedstock Flexibility Data on H_2 LDES - AES Power Consumption

The team tested the effects of simulated dilute H_2 waste stream compositions on AES power consumption. From the team's survey of syngas sources in California there are two major diluents present in the syngas:

1. CO_2: Typically depends on gasifier design and biomass composition (CO_2 can be 20 to 50 percent)
2. N_2: Typically, representative of air-blown gasifier process (N_2 can be 20 to 50 percent)

The T2M team has tested AES performance on 75 percent and 90 percent N_2 or CO_2 as diluent. The results are presented in **Figure 22**. As expected from the theoretical Nernst equation, the data shows that the dilution of anode hydrogen flow with either N_2 or CO_2 results in the lowering of stack Open Circuit Voltage compared to the base case with 100 percent H_2. However, as current is applied to the stack, the H_2 production rate is increased, and the power consumption curves for N_2 and CO_2 differ. For the N_2 curves, they are offset by their differences in Open Circuit Voltage but otherwise have effectively the same slope. The CO_2 curves also show a linear behavior but with a slightly higher slope. Since this effect is evident in the CO_2 data from low to high current densities, it appears that the anode is still in a linear Butler-Volmer regime, but with higher non-ohmic area-specific resistance. That is, the kinetics in CO_2 are slower than those in N_2. A potential cause for this is the reverse-water-gas-shift reaction where CO_2 + H_2 is being converted into CO and H_2O.

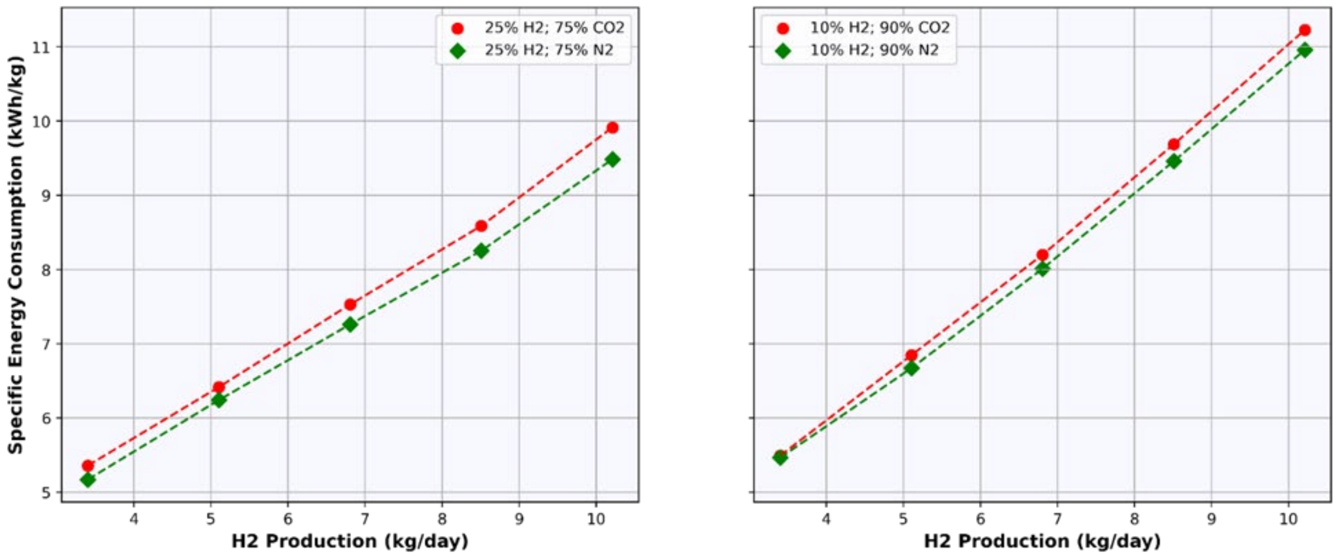
Figure 22 validates ultra-low energy consumption for different dilute/waste H_2 streams during the charging cycle of energy storage. It confirms that AES technology met the CEC program stretch goal of less than 10 kWh/kg.

Figure 23 compares AES power consumption for different H_2 concentrations (10 to 100 percent). Power consumption increases slightly as the H_2 concentration decreases. Especially at 10 percent H_2, the increase in power consumption becomes non-linear.

Figure 23 also shows the effect of increasing H_2 production rate, as represented by current density. A greater H_2 production rate means reduced CapEx of AES. This data was used in the scale-up to 100 kg/day building block described later.

It also establishes readiness to scale up to 100 kg/day building block.

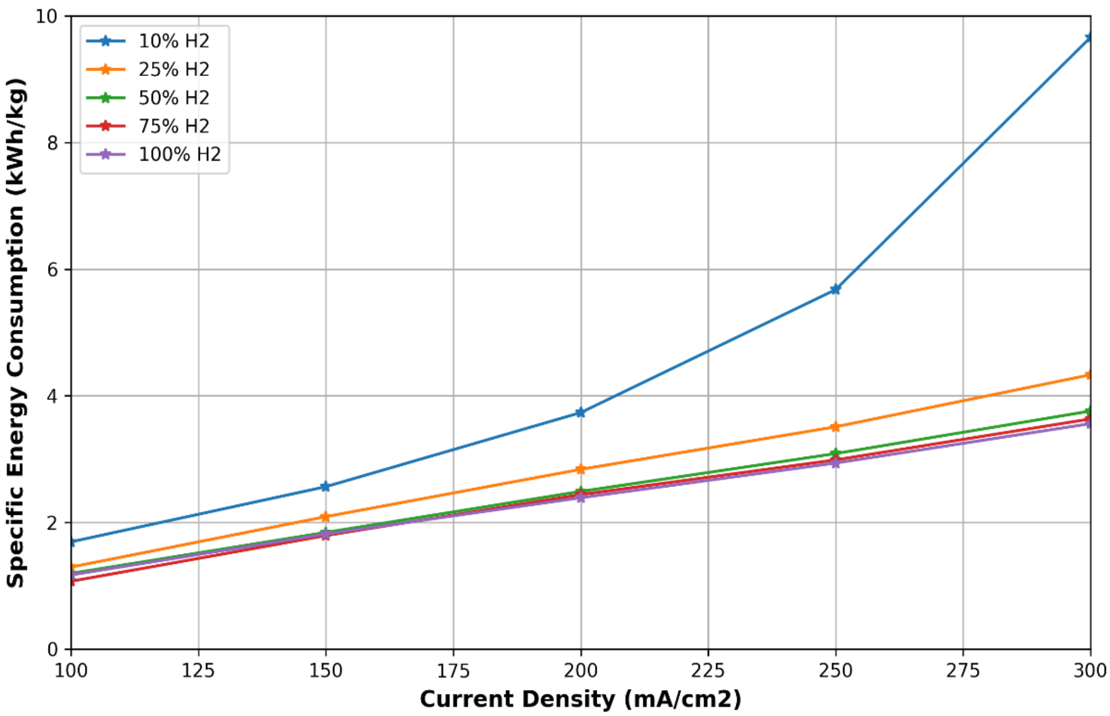
Figure 22. Validated Feedstock Flexibility – Dilute H_2 Streams



Met CEC project stretch target for electricity consumption: less than 10 kWh/kg H_2.

Source: T2M Global

Figure 23. Effect of Dilution on AES Performance



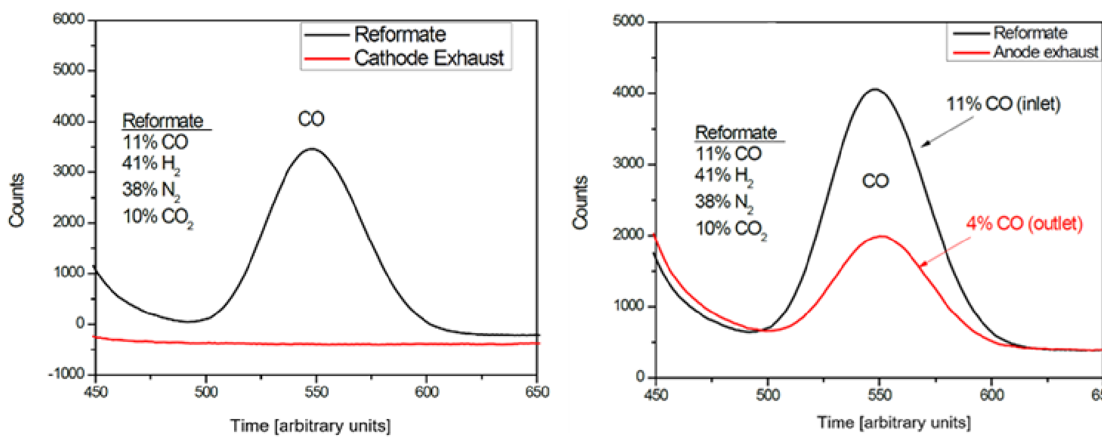
Specific energy consumption increases with feedstock dilution and H_2 production rate.

Source: T2M Global

Feedstock Flexibility—Contaminant Tolerance (For Example, Carbon Monoxide)

Some dilute/waste H_2 streams may contain 1 to 30 percent CO as an impurity that may adversely impact efficiency of the charging cycle. There is a concern that these impurities in the syngas, especially carbon monoxide, can adversely affect the purity of the product H_2. To address this concern, we tested an AES cell with simulated dilute syngas with 11 percent CO as feedstock (reformate at anode in, **Figure 24**). Gas samples were taken from the anode side inlet for the feed composition and cathode side outlet for hydrogen product purity and analyzed. As can be seen from **Figure 24a**, there was no CO detected in the product H_2 (cathode outlet). This indicates excellent integrity of the electrochemical membrane used for hydrogen production via advanced electrolysis. **Figure 24b** shows the CO concentration measured at the anode outlet compared to the anode inlet: CO concentration is reduced from 11 percent to 4 percent, indicating a corresponding increase in hydrogen by 7 percent. T2M believes this beneficial feature can significantly increase hydrogen production from AES operating on CO-containing dilute/waste H_2 streams.

Figure 24. Effect of CO on AES Performance



(a) Good hydrogen product purity (no CO, shown in red).

(b) CO converted to additional hydrogen.

AES has the capability to internally shift CO to additional hydrogen.

Source: T2M Global

Validating Benefits of Pressurized Operation

Pressurized operation has multiple benefits for H_2 LDES:

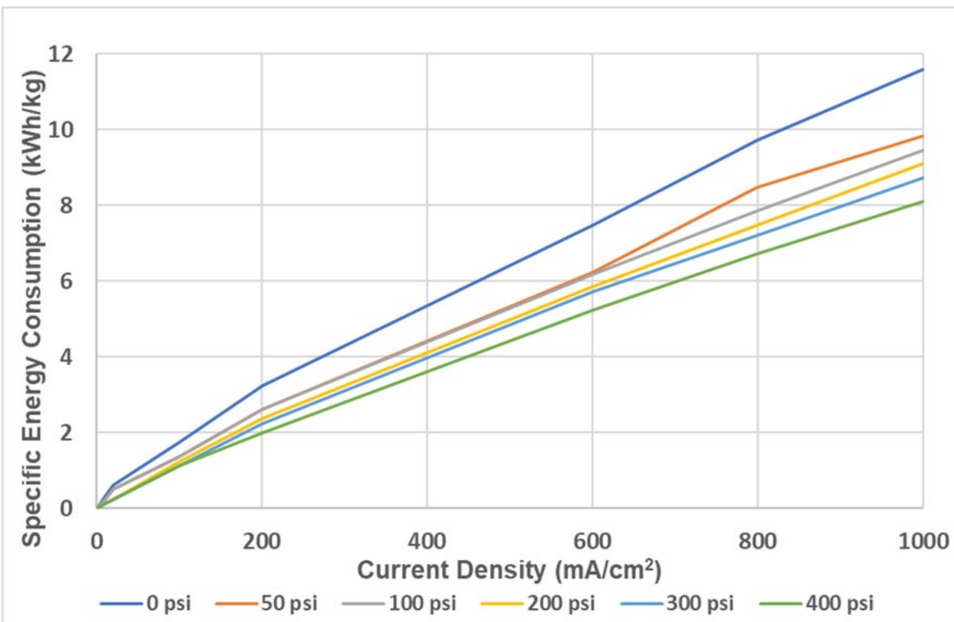
- Increased round-trip efficiency for electrolytic H_2 LDES, which is very important for the EPIC Program and grid support needed for the transition to a zero-emission economy.
- Reduced energy consumption, hence lower cost H_2.
- Increased H_2 production rate, hence lower capital cost.
- Improved compatibility with H_2 station storage and dispensing, reduced operating cost.
- Overall, reduced CapEx and OpEx leads to competitive LCOS of less than 5 cents/kWh.

To validate the above benefits, we conducted parametric testing of AES at different operating conditions. **Figure 25** below shows the effect of pressure and H_2 production rate (current density) on the specific energy consumption of H_2 production. The operating pressure was increased from 0 psi to 400 psi with measurements taken at different production rates. A corresponding decrease in the specific energy consumption was measured and analyzed for the 100 kW-class building block design and technoeconomic analyses. The following are key observations that make LDES even more attractive with pressurization:

- The energy consumption in all these cases remained below the CEC project target of less than 15 kWh/kg H_2 – making it attractive for LDES application.
- Pressurization to 400 psi reduces specific energy consumption by about 30 percent.
- Pressurization enables increased H_2 production rate – from 200 to 1,000 mA/cm^2.
- This translates to potential cost savings of up to 80 percent.
- With these attractive benefits, further scaleup of AES technology is highly warranted.

Figure 25 should be interpreted as a trade-off between capital and operating cost of the AES module. Increased pressure capability reduces the operating cost, that is, the specific energy consumption of AES, but increases the initial capital cost to make the AES module and the associated electrical and mechanical balance of plant pressure capable.

Figure 25. Benefits of Pressurized Operation of AES



Power consumption decreases at elevated pressures.

Source: T2M Global

Durability Testing: 2,500 Hours of Operation Demonstrated

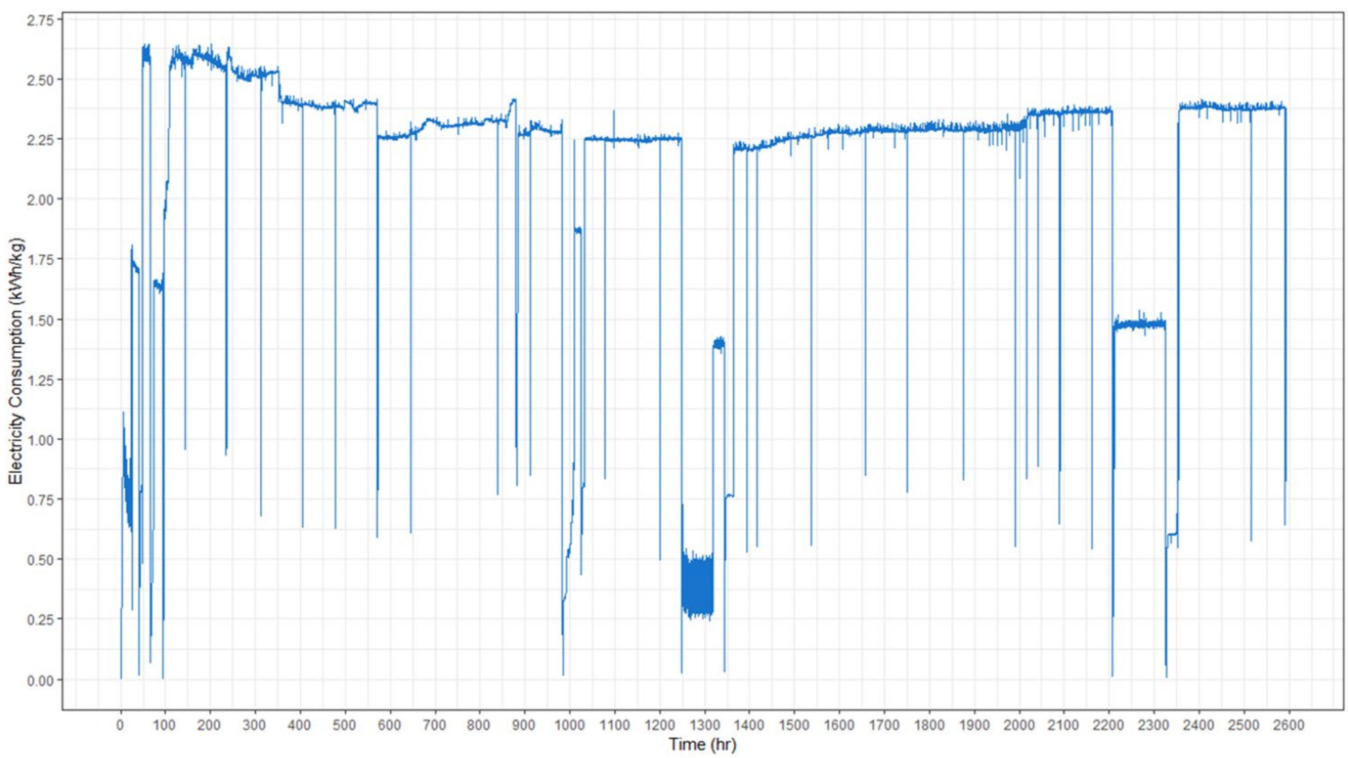
The objective of the durability testing was to provide performance and stability data needed for AES system design, scale-up, and technoeconomic analyses. Improvements were made to the test station for unattended operation. This included enhancements in the humidification system based on lessons learned from previous AES pressurized operation tests. AES durability tests were conducted at the initial goal of 500 hours of operation. With the highly encouraging results from this initial test, we performed extended durability test to 2,500 hours with similarly encouraging results, **Figure 26**.

During durability testing, we performed H_2 purification in a single-step as a way to dramatically reduce CapEx and OpEx for H_2 LDES. The team conducted long-term testing of AES at varying compression levels. Test results showing energy consumption over time for different operating conditions are shown in **Figure 26**. Major observations were:

- The excellent stability of performance validates viability for commercial application.
- H_2 purification plus compression in a single stage was successfully validated – up to 60 psi. This opens pathways for further system simplification and cost reduction for LDES.
- The solid-state device eliminates moving components, offering greater reliability and lower maintenance costs.
- The energy consumption during all durability tests remained below 5 kWh/kg, indicating potential for further reduction from the stretch goal of 10 kWh/kg.

The electricity consumption is expected to increase somewhat for the entire AES system, which will include AES building blocks with multiple stacks, E-BOP and M-BOP.

Figure 26. AES Durability Testing



H_2 purification and compression in a single device: up to 60 psi operation.

Source: T2M Global

100 kg/day Building Block

Existing Cell Hardware: The cells in the AES stack used in this testing were of T2M's standard dimensions, leading to up to 5 kg/day of H2 generation. Use of this hardware would require 20 stacks for a 100 kg/day building block. This would require additional manifolds for the 20 stacks and management of the associated complexity for flow distribution, mechanical supports, and electrical isolation. Due to this complexity and other factors, this design has been deemed infeasible for commercial production. The team focused on increasing cell area using alternate supply chains.

Larger Capacity Hardware: Addressing the above cost drivers requires trade-offs between larger area cell components and supply chain limitations. Larger area cells increase H2 production capacity linearly. However, the technology and manufacturing risks increase as the cell area increases. The technology validation must be done prior to committing manufacturing of larger capacity hardware. The following factors contribute significantly to the 100 kg/day building block performance and cost:

- Cell Area: Larger area is better, but tolerance management and supply chain are crucial.
- Operating Current Density: Greater current density is preferred, but thermal management complexity increases at higher current densities.
- Stack Height: Greater number of cells/stack is beneficial; however, component tolerance management becomes more complex as stack height increases.

Table 5 summarizes the parametric trade-off analyses performed for the above cost contributing factors. The project experienced some supply chain issues due to the uncertainties of the COVID-19 pandemic. T2M selected the following strategy for the building block:

- Near-term: Existing supply chain, 1,000 cm^2 cell area
- Commercial: Alternate supply chain, 3,000 cm^2 cell area

The highlighted data in **Table 5** corresponds to the tall stack design capable of producing nominally 100 kg/day in the near-term and 300 kg/day for the commercial module.

Table 5. Increasing Tall Stack H_2 Production Capacity

Current Density	Number of Cells	Cell Area: 200 cm^2 H_2 Production Rate	Cell Area: 500 cm^2 H_2 Production Rate	Cell Area: 1,000 cm^2 H_2 Production Rate	Cell Area: 3,000 cm^2 H_2 Production Rate
mA/cm^2	cells/stack	kg/day	kg/day	kg/day	kg/day
				Near Term	Commercial
200	200	6.99	17.47	34.94	104.84
	300	10.48	26.21	52.42	157.25
	400	13.98	34.94	69.89	209.67

Current Density	Number of Cells	Cell Area: 200 cm^2 H_2 Production Rate	Cell Area: 500 cm^2 H_2 Production Rate	Cell Area: 1,000 cm^2 H_2 Production Rate	Cell Area: 3,000 cm^2 H_2 Production Rate
	500	17.47	43.68	87.36	262.09
300	200	10.48	26.21	52.42	157.25
	300	15.73	39.31	78.63	235.88
	400	20.97	52.42	104.84	314.51
	500	26.21	65.52	131.05	393.14
400	200	13.98	34.95	69.89	209.67
	300	20.97	52.42	104.84	314.51
	400	27.96	69.89	139.78	419.34
	500	34.95	87.36	174.73	524.18

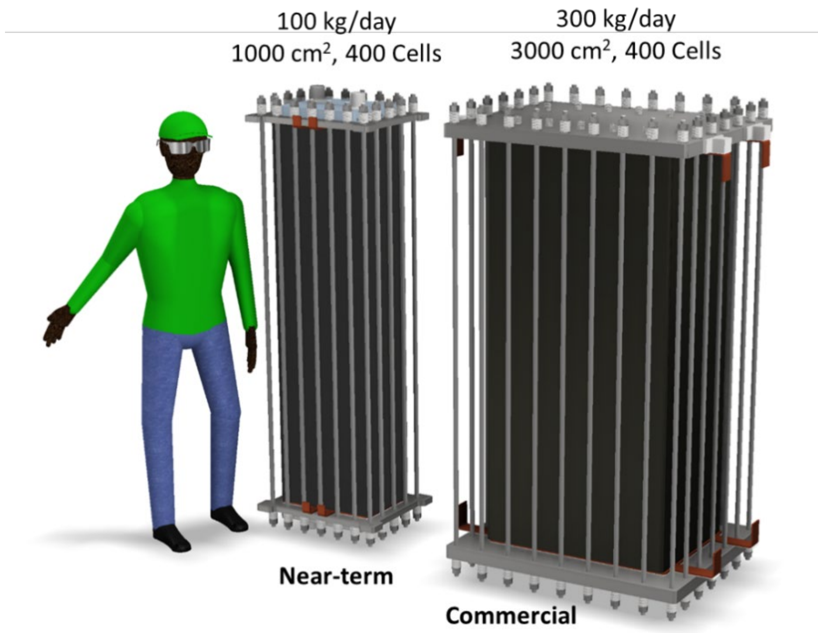
100 kg/day building block design completed: near-term vs. commercial.

Source: T2M Global

Three-dimensional renderings of the near-term and commercial building block designs are shown in **Figure 27** below. The near-term design with 400 cells/stack operating at 300 mA/cm^2 is estimated to produce about 105 kg/day of H_2. The commercial design employs three times larger area cells; hence, three times larger production capacity for H_2. This translates to about 315 kg/day H_2 for the commercial building block. The project team initiated outreach to current supply chain contacts for the larger capacity hardware components. **Figure 28** shows the major assembly steps starting with a single cell assembly, tall stack assembly, manifolding installation, and stack with multi-purpose enclosure. The team analyzed strategic advantages of buy versus make options, and also made a preliminary assessment to manufacture AES in California. These are the components necessary to source for production readiness:

- AES cell: Membrane-electrode-assembly, bi-polar plates, gaskets.
- Stack hardware: Endplates, compression hardware, dielectrics, electrical bus bar.
- Stack assembly: Manifolds, piping, sensors.
- Enclosure: All-weather container, penetration hardware, shipping and handling.
- E-BOP: Power supply, control system, safety system.
- M-BOP: Gas metering, valves, pumps, vessels, sensors, coolant loop, heat exchangers.

Figure 27. AES Building Block → Near-term and Commercial



Established supply chain for the near-term allows rapid deployment for H_2 energy storage.

Source: T2M Global

Figure 28. AES Cell to 315 kg/day Stack in Multi-purpose Enclosure

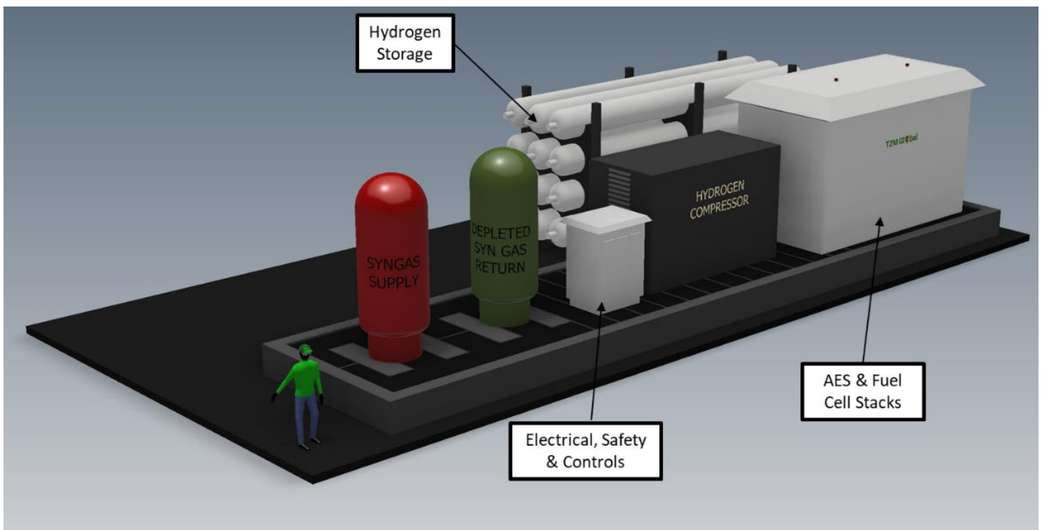
Modular plug-and-play design for rapid deployment.

Source: T2M Global

Long Duration Hydrogen Storage

As discussed earlier in Chapter 2, Project Approach, H_2 storage becomes more attractive than conventional lithium-ion battery storage for durations greater than eight hours. **Figure 29** shows a conceptual design for a complete 100 kW-class AES-H_2 storage. It shows major components of the system along with H_2 storage. This system is designed for 100 kg/day H_2 production. That is equivalent to 2.4 MWh of electricity storage. This is equivalent to about one week of storage. Storage capacity can be further increased by installing additional storage cylinders for H_2. This very low incremental cost is the reason why H_2 LDES becomes more attractive for longer durations. At MW-scale, the H_2 LDES becomes more competitive. As discussed later in the technoeconomic analyses for commercial-scale deployment, the AES-H_2 offers LCOS of less than 5 cents/kWh.

Figure 29. AES-H_2 Energy Storage - Complete 100 kW System



Integrated system with small footprint: about 7 days of LDES.

Source: T2M Global

Strategy for Manufacturing AES in California

For this project, T2M investigated the initial feasibility of setting up an assembly plant for AES in California. The team also explored sourcing of supply chain for key components in California and elsewhere in the U.S. T2M's near-term module design reflects the California supply chain.

Summary of supply chain from California:

- The E-BOP supply chain is well-developed in California.
- The M-BOP supply chain is available: cost-effectiveness needs to be addressed.
- AES cell: membrane electrode assembly supply is possible. However, the cell size and production capacity need investment to support commercial-scale deployment.
- Vessel fabrication supply chain contacts are initiated.
- Assembly plant: Locating the AES assembly plant in California is ideal as the permitting process will be streamlined due to the benign nature of AES stack and system

components. Additionally, the well-established supply chain in California is synergistic with AES production. This would generate high-paying jobs and benefit disadvantaged communities in California.

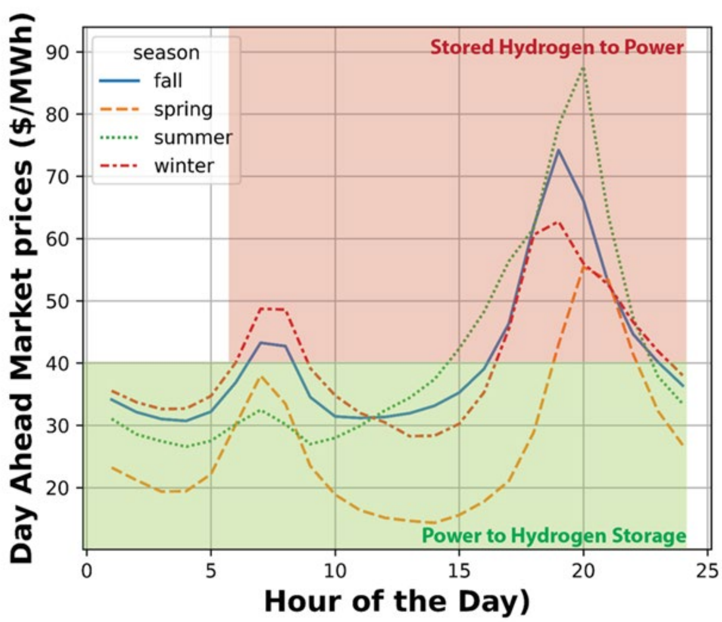
Cost Estimates and Technoeconomic Analysis

California's ambitious targets for going green have resulted in increased penetration of solar and wind electricity. These renewables are intermittent. Every 100 kW of green electricity may require as much as 50 percent of that in energy storage to manage grid instability. Hydrogen energy storage is very promising for long duration applications (longer than eight hours: where batteries get too expensive to deploy). The cost of hydrogen produced using AES is very important for economic viability. The following parameters are potential contributors to the H_2 production cost:

- Capital cost: Cost of AES equipment for hydrogen production and storage.
- Operating cost: Feedstock costs, such as the renewable electricity cost and syngas cost.
- Maintenance cost: Life of AES stack, BOP hardware, etc.

The T2M team analyzed the impacts of feedstock, electricity, and capital costs on the H_2 production cost. The daytime excess solar electricity in California often leads to curtailments of as much as 10,000 MWh/day. This leads to negative pricing. The T2M team did not assume negative electricity cost in this analysis. The electricity cost to power AES will likely be in the low range. The range of syngas cost included \$0 to \$5 per million British thermal units (MBTU). Based on the data analysis shown in **Figure 30** and Commission Agreement Manager input, the team analyzed the sensitivity of the cost of syngas on the cost of H_2 for three scenarios for renewable electricity costs: 1, 5, and 10 cents/kWh.

Figure 30. Wholesale Renewable Electricity Prices Analyzed Seasonally



Average electricity prices vary from 1 cent/kWh to 9 cents/kWh.

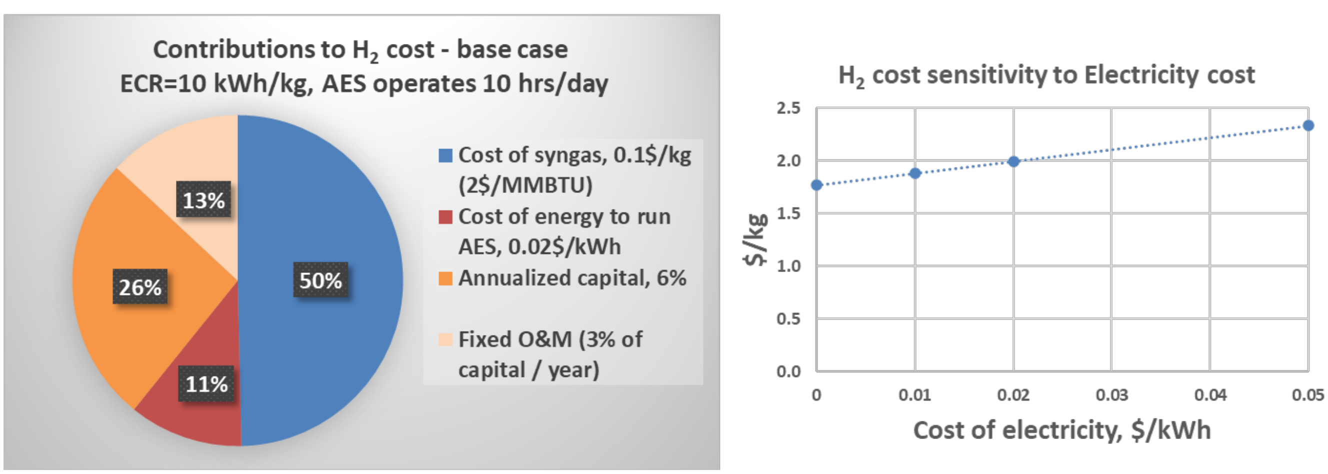
Source: California ISO

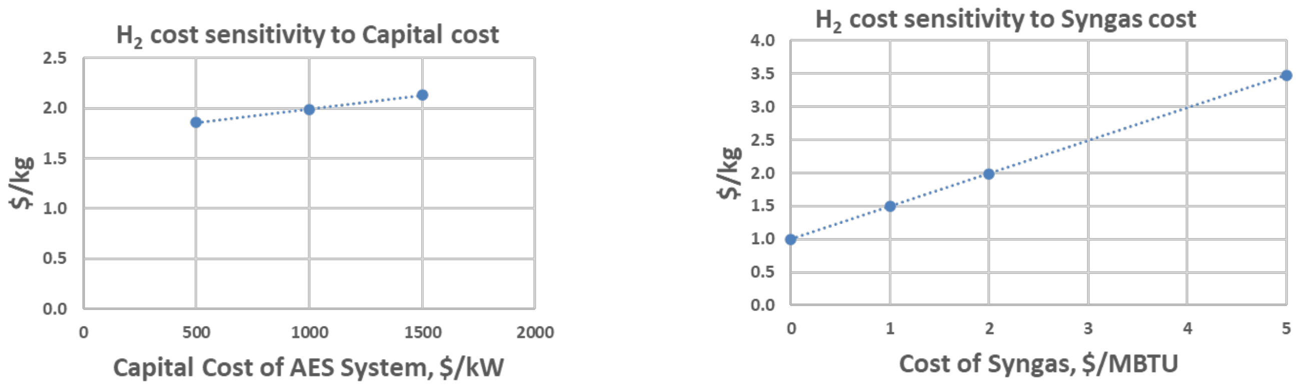
A similar analysis was also performed for varying capital costs: \$500/kW, \$1,000/kW, and \$1,500/kW. The \$1,500/kW capital cost represents near-term cost of LDES using AES-H_2. As LDES system deployment increases, the cost of AES system is expected to decrease due to volume mass production. The \$500/kW represents capital cost at full-scale deployment. This cost reduction is anticipated from recent projections by DOE as well (Satyapal , 2023). The results of these parametric analyses are shown in **Figures 31, 32, 33, and 34** with the following observations for the value proposition offered by the AES-H_2 for LDES applications:

- The H_2 production cost at \$1,000/kW of AES capital cost, renewable electricity input cost of 2 cents per kWh, and syngas cost of \$3/MBTU was estimated to be about \$2.50 per kg H_2 - significantly better than the target of the project, less than \$4/kg (**Figure 31**).
- The H_2 cost decreases further to \$2/kg H_2 when electricity is available at 2 cents/kWh - a likely scenario in daytime hours during spring months (**Figure 32**).
- The H_2 cost reduces to \$1/kg H_2 when the syngas is available at no cost: a likely scenario for wasted streams in large plants with cooling towers.
- In a fully commercialized scenario, T2M expects AES capital cost to approach \$500/kW. In this case, H_2 cost decreases to less than \$2/kg: highly competitive for LDES.
- In all cases analyzed, LCOS of less than 10 cents/kWh is projected for the near-term higher capital cost scenario, **Figure 33.**
- Overall, LCOS of less than 5 cents/kWh is achievable with full-scale deployment in LDES markets (**Figure 33**).
- **Figure 34**, derived from DOE National Renewable Energy Laboratory (NREL) study (Augustine and Bair, n.d.), compares different energy storage technologies. As the duration of storage increases, the normalized cost for storage increases linearly for battery-based storage technologies. The capital cost of AES-H_2, as shown in **Figure 34**, does not increase with the duration of the storage.

These versatile features make AES-H_2 a very promising and attractive technology for LDES applications.

Figure 31. Cost Estimates for H_2 Energy Storage

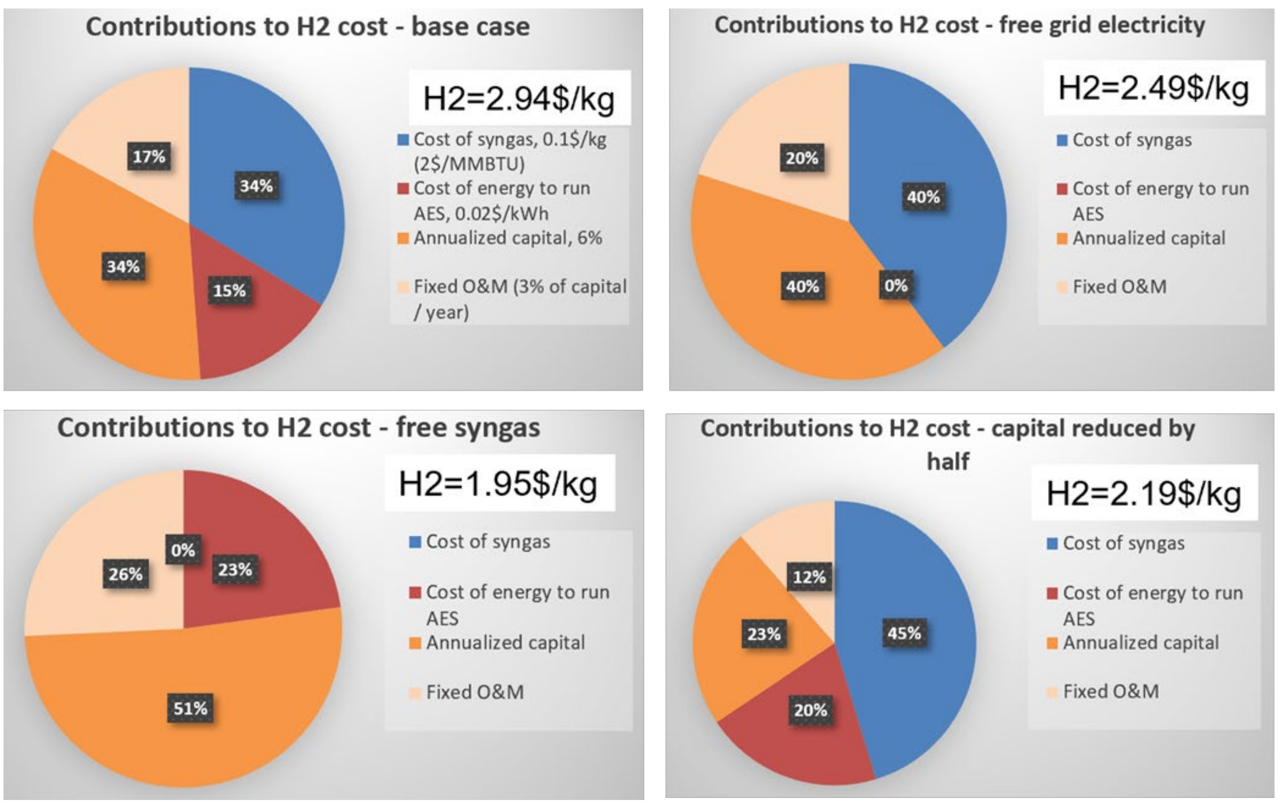




Met CEC program goal of less than $4/kg H_2.

Source: T2M Global

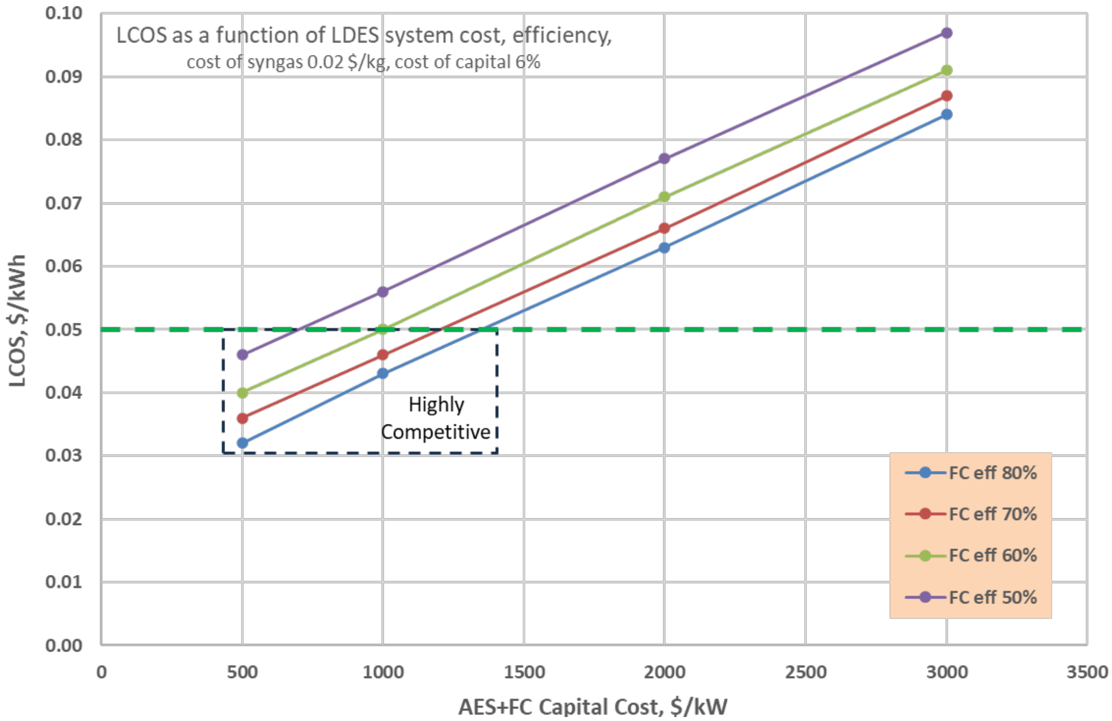
Figure 32. Parametric Analysis - Strategy to Reduce H_2 Production Cost



Identified pathway to further reduce H_2 cost to less than $2/kg.

Source: T2M Global

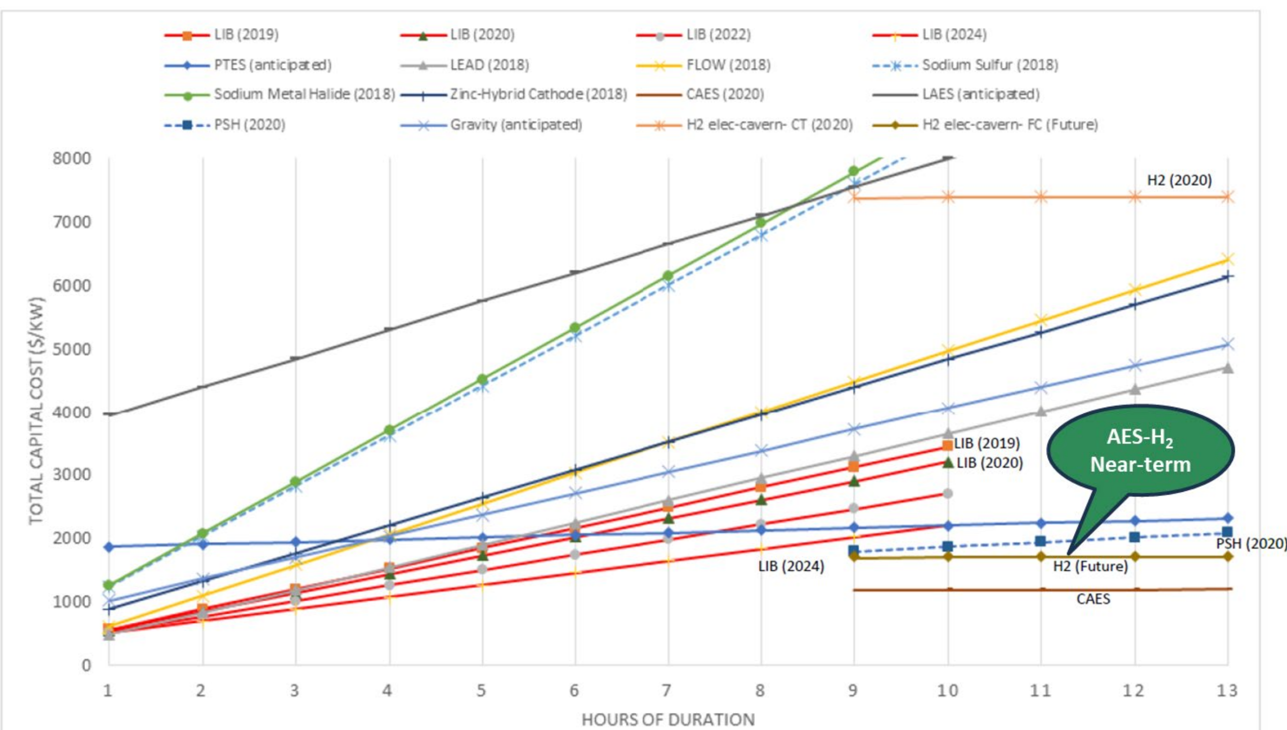
Figure 33. LCOS for AES-H_2



LCOS of less than 5 cents/kWh is achievable at full-scale deployment.

Source: T2M Global

Figure 34. Capital Cost vs. Duration for Energy Storage Technologies



For LDES, AES-H_2 storage offers a highly promising option at MW-scale.

Source: NREL Storage Futures Study and T2M Global for AES

Response Time Comparison – Battery vs. Hydrogen

The AES module takes about 40 minutes on average to ramp up from a cold start to power production mode. Once the system is in power production mode, it has a very fast response time of about 500 W/minute for ramp-up and instantaneous ramp-down capability. The response time is significantly improved with the coupling of a battery bank. With the battery bank, the system can ramp up from zero load to 7 kW within a second. The battery bank also improves the load-following capability of the AES module. Overall, a hybrid energy storage system will have better performance and lower cost for both short- as well as long-duration applications.

Technical Barriers and Challenges Faced in the Project

The feasibility of electrolytic H_2 energy storage using AES technology for the charge cycle has been demonstrated successfully. The technology scale-up from less than 1 kg/day level to 5 kg/day was achieved and validated. The lab testing results and parametric sensitivity analysis show that a round-trip efficiency of more than80 percent and H_2 production cost of less than $4/kg is achievable. The further scale up to a 100 kg/day building block needed for a MW-class module needs to resolve the following technical barriers and challenges:

- Technology scale-up: Further increase in cell area is critical to reduce costs.
- System integration with the host site: limited space may require engineered access for AES installation for energy storage benefits.
- LDES: needs greater H_2 storage volume and pressure; requirements of permitting and code compliance may increase footprint and cost.
- Thermal integration: use of waste heat from AES to supplement on-site boiler.
- Confidential data: access to dilute/waste H_2 streams data from potential early adopters.

Key Lessons Learned

- The round-trip efficiency of H_2 energy storage can be increased from less than 40 percent to more than 90 percent by using waste/dilute H_2 streams as H_2 carrier.
- Hybrid energy storage to complement rapid response battery storage with range extending H_2 energy storage is a highly versatile solution for renewables.
- The AES technology is scalable and modular for phased capacity expansion.
- Pressurized operation can reduce operating cost by about 30 percent while reducing footprint by more than 50 percent.
- CO containing dilute H_2 streams may pose additional safety issues. However, a smart system integration to convert CO to CO_2 and produce more H_2 is feasible.
- AES-H_2 storage coupled with a fuel cell has rapid response to support microgrids, for both AC and DC applications.
- The AES technology has the potential to create higher value H_2 from dilute waste streams. It can provide a win-win solution to forest fires by utilizing forestry waste to

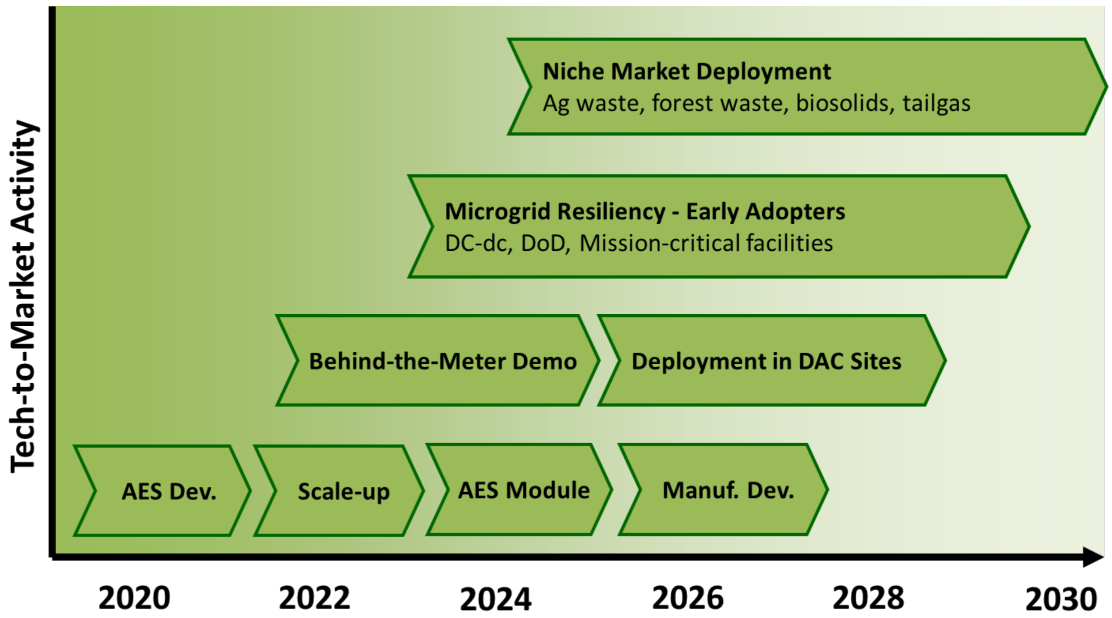
produce green H_2 for multiple applications such as LDES, EV charging in the evenings, and providing H_2 infrastructure for the zero-emission economy.

Future Research and Development Opportunities

The results of AES-H_2 for LDES project are highly promising. T2M developed a near-term technology development and demonstration plan to commercialize this technology as illustrated in **Figure 35**. The following Research and Development (R&D) opportunities have been identified to reduce technology risk and attract private sector investment needed for commercialization:

- Scale up and validate a 100 kW AES building block.
- Field demonstration of the 100-kW class building block at high value microgrid sites.
- Further scaleup to a MW-class prototype: module designed for manufacturing.
- Develop and validate Multi-Purpose Energy Station for EV-charging and grid support.
- Engage IOU and California ISO stakeholders to develop and demonstrate the value proposition of MW-class H_2 energy storage to meet ambitious California mandates.
- Demonstrate cross-cutting applications using the AES-H_2 solution to mitigate forest fire risks while providing multiple GWs of energy storage, as shown in **Figure 36**.
- Demonstrate cross-cutting application using AES-H_2 solution for microgrid support and upgrading of liquid biofuels to leverage CEC investments, **Figure 37**.
- Deployment plan: manufacturing development for AES to meet near-term customer needs: supply chain, production lines, assembly plant for early production units.
- Behind the Meter demonstration: gas industry and aggregator partnership for monetization.
- Early adopters seeding in niche markets, for example:
  - DC Microgrids for data centers.
  - Grid Resiliency: PG&E Woodyards: gasifier → H_2 storage (MW module).
  - LDES for DOD sites having existing biomass gasifiers.
  - Hybrid energy storage system: EPRI, IOUs, California ISO.
  - Flare gas sites in the Los Angeles area, Oakland, and Fremont: Air Quality Management District, Waste Management.
  - Fuel cell tail gas: example Toyota at Port of Long Beach, Bloom Energy.
  - Biogas RNG sites: use of tail gas for H_2 storage.

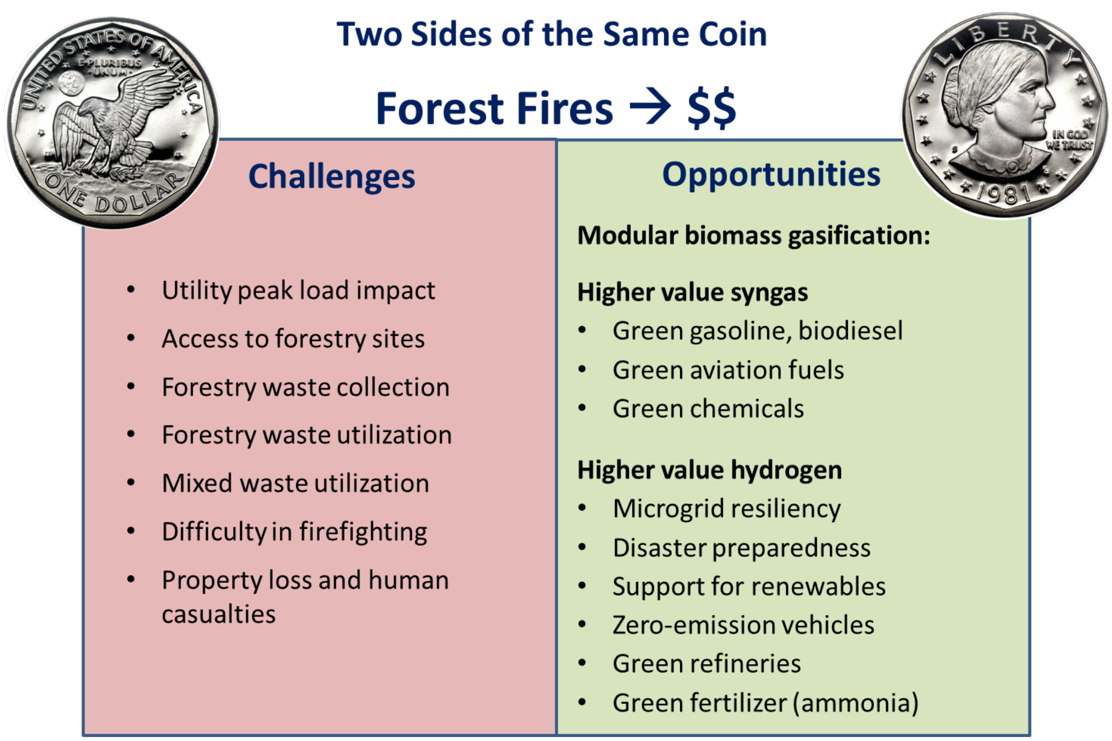
Figure 35. Roadmap for AES Commercialization



Next steps – Technology scale-up and demonstration at MW level. Note that DAC stands for disadvantaged community.

Source: T2M Global

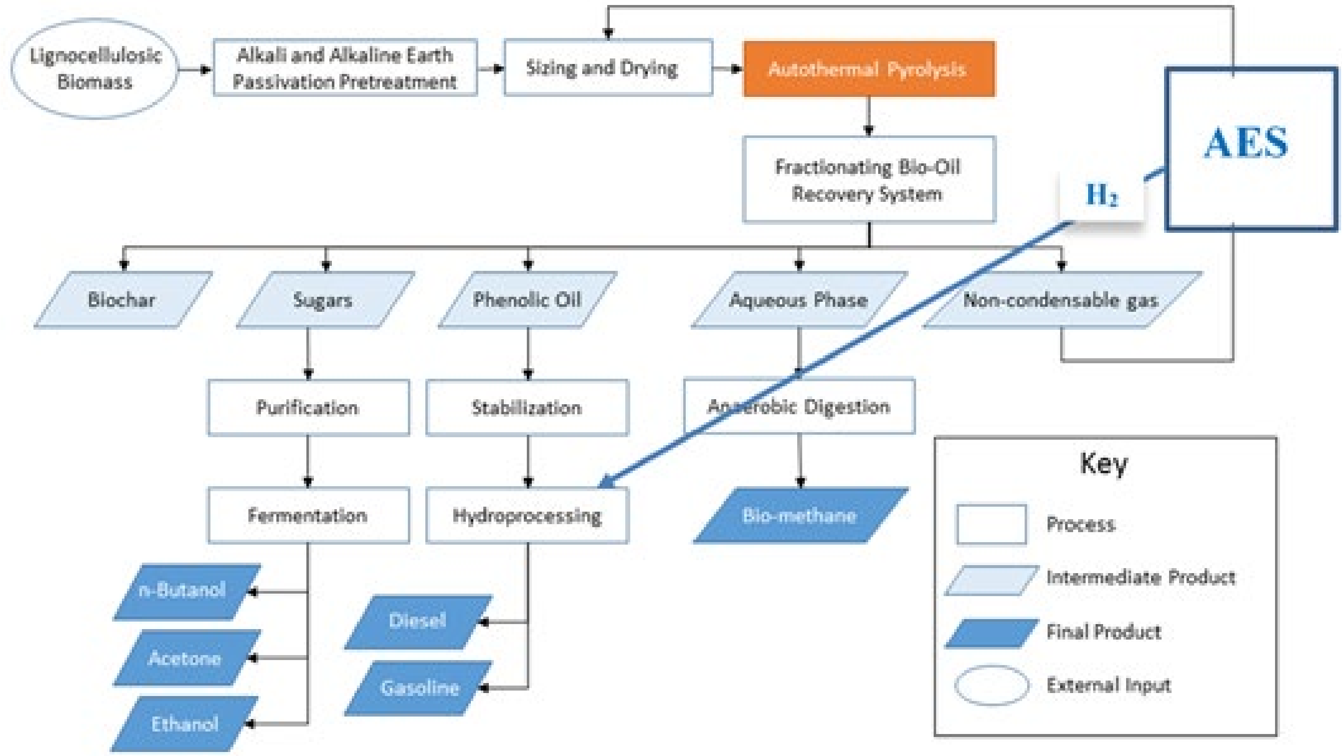
Figure 36. Opportunity to Mitigate California Challenges Using Green H_2



Reduced forest fire risk → feedstock for H_2 energy storage.

Source: T2M Global

Figure 37. Multipurpose Solution for Cross-cutting Applications



H_2 energy storage for microgrid support and upgrading liquid biofuels.

Source: T2M Global

Technology Transfer and Outreach for AES-H_2

Details of the technology transfer and outreach activities are submitted to CEC in a separate deliverable report. Highlights of these activities are presented here. The T2M team successfully performed extensive outreach to major stakeholders and TAC members to develop market-responsive AES technology and its deployment strategy in California. The following outreach for knowledge transfer of AES provided valuable guidance:

- Strategic Alliances: IOUs: PG&E and SoCal Gas; California ISO; California Universities; South Coast Air Quality Management District (SCAQMD).
- Sponsoring Agencies: DOE, DOD, CEC, CARB, EPRI, Gas Technology Institute, Ports, California Highway Patrol Centers.
- Investment Partners: Private and public sponsors.
- Demonstration partners: Identified potential early adopters in California.
- Microgrid Market Partners: EV charging, aggregators, and gas industry.
- Supply Chain: Manufacturing of cell, stack, and system components in California.
- Conferences: CleanTech Open, VERGE Energy, Shell GameChanger Accelerator Powered by NREL, DOE Advanced Manufacturing Office, CEC EPIC.
- Trade Associations: California Hydrogen Business Council (CHBC), California Bioenergy.

Outreach Methods, Platforms and Metrics

CleanTech Open – Western: Investors Mixer in Oakland

The T2M team, highlighted in **Figure 38**, engaged directly with clean technology investors, policymakers, and other stakeholders such as electric and gas utilities at the CleanTech Open national conference. CleanTech Open finds, funds, and fosters the most promising cleantech startups on the planet. It was a perfect venue for targeted outreach of AES technology to key stakeholders.

Figure 38. Outreach to CleanTech Investor Community

VERGE Conference – Oakland, Bay Area

Source: T2M Global

Outreach to Microgrid Stakeholders

The following virtues of the Electrolytic H_2 Storage Solution were communicated to California microgrid stakeholders, **Figure 39**:

- Versatile for Deployment in Multiple Market Segments: EV charging, grid support services.
- Compatible with DC-Microgrids: Data centers, solar PV, and wind experience 10 to 20 percent electrical losses between DC-AC conversion. AES-H_2 storage eliminates these losses.
- Easier Permitting and Insurance Approval: O_2-free storage for greater safety.

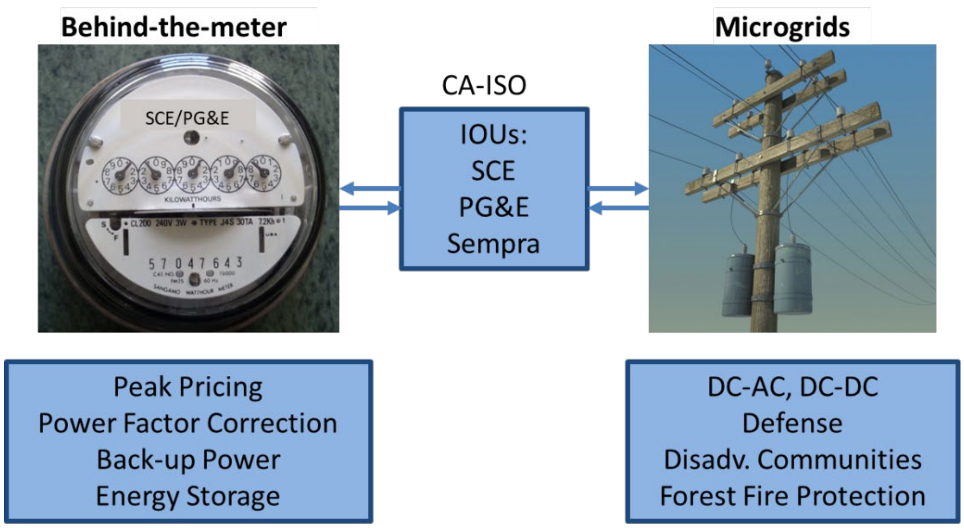
The T2M team conducted outreach for H_2 energy storage in the two major scenario applications:

1. **Customer side of the meter — led by the gas industry**: The current R&D portfolio for advanced green natural gas technologies includes several new technologies and pathways. T2M received input from the project's TAC members from the gas industry to identify potential opportunities for AES to enhance the value proposition of these technologies. Several opportunities have been identified where dilute syngas is a wasted

resource. The team plans to pursue this further within the permissible boundaries of intellectual property protection.

2. **Utility side of the meter — led by electric utilities:** There is a need for utility scale hydrogen storage to manage electricity variation in the GWh range. The current variations are between 5 to 25 GWh. One possible scenario is Power to Gas (P2G). This includes storing excess electricity as H_2 and the injection into the natural gas pipeline, which may be in the range of 5 to 15 percent hydrogen.

Figure 39. H_2 Storage for Customer Side of the Meter or Export to Microgrid



Value offered to stakeholders of multipurpose microgrids.

Source: T2M Global

2020 EPIC Survey: T2M completed the 2020 EPIC survey, providing feedback to CEC on enhancing the value of CEC's investments and the advancements it has led to. Here is an extract/summary from the team's response:

"Hydrogen has been a key component for CO_2-free transportation and stationary power, especially for disadvantaged and EJ Communities. Hydrogen energy storage is a multi-purpose solution for enhanced grid reliability, as well as charging of Battery Electric Vehicles. It will also support Fuel Cell Electric Vehicles, including trucks, buses, cars, and port vehicles. Hydrogen infrastructure has been identified as a key opportunity to meet many of the regulatory codes and standards. Dilute syngas streams are typically wasted and contribute to emissions. These can be monetized by deployment of the AES Technology."

Presentations at Key Conferences

- California Hydrogen Business Council (CHBC) Clean Ports: Role of H_2 LDES in Port Electrification to improve air quality, 2022.
- Port of the Future: Chaired session on H_2 LDES for Houston area ports, 2021.
- Nitrogen + Syngas conference: Role of H_2 LDES for Ammonia economy, 2022.
- CEC Microgrid conference: Provided input for AES-H_2 to support LDES, 2022.

Outreach to Hydrogen Industry

Among major hydrogen producers in California, the team performed outreach to Air Products and Chemicals, Air Liquide, and Linde-Praxair. Among refineries, collaborative outreach included Tesoro, Chevron, Exxon, and Shell. Among major fuel cell vehicle developers, T2M's interactions included hydrogen infrastructure solutions for Toyota, Honda in California, and GM in Hawaii.

Trade Association Membership

California Hydrogen Business Council (CHBC): T2M's President was elected to CHBC's Board in December 2021. Cost-effective production of green H2 is an important goal set by California mandates. As a Board member, T2M's President has access to industrial and manufacturing stakeholders in the hydrogen economy, which can benefit greatly by the integration of AES-H_2 technology for LDES. The press release for this election is shown in Appendix A.

On-line resources[11]

Outreach through T2M Global Website: Technology section, news section and home page.

Fact sheets

Fact sheets were provided to stakeholders to promote technology benefits, gain feedback from potential early adopters, and promote investments in scale-up. The fact sheet can be seen in **Appendix B**.

T2M provided input to CHBC for their fact sheet for Electrolytic Hydrogen for Energy Storage. It is entitled "Electrolytic Hydrogen: Enabling Deep Decarbonization by Harnessing and Storing Renewable and Zero-Carbon Power." It illustrates the potential uses of green hydrogen made from excess renewable electricity from intermittent renewable power sources (solar, wind).

Policy Barriers

Recent climate-change driven events have led to significant policy improvements for the low-carbon economy, ultimately leading to zero-carbon by 2050. However, during the transition phase, there are policy barriers that limit the role of H_2 storage for LDES applications:

- Use of wasted resources for energy storage is not recognized as a pathway to support the transition to renewables.
- AES-H_2 produces no criteria pollutant emissions. There is no blanket permit for rapid deployment in California.
- Deployment in disadvantaged communities, low-income communities, and EJ communities is highly beneficial. However, there is no simple financial incentive to promote it.
- Clean electricity derived from wasted/dilute H_2 streams is not yet deemed as renewable. **Figure 40** shows the potential of up to 2 million metric tons/year nationwide for H_2 LDES.

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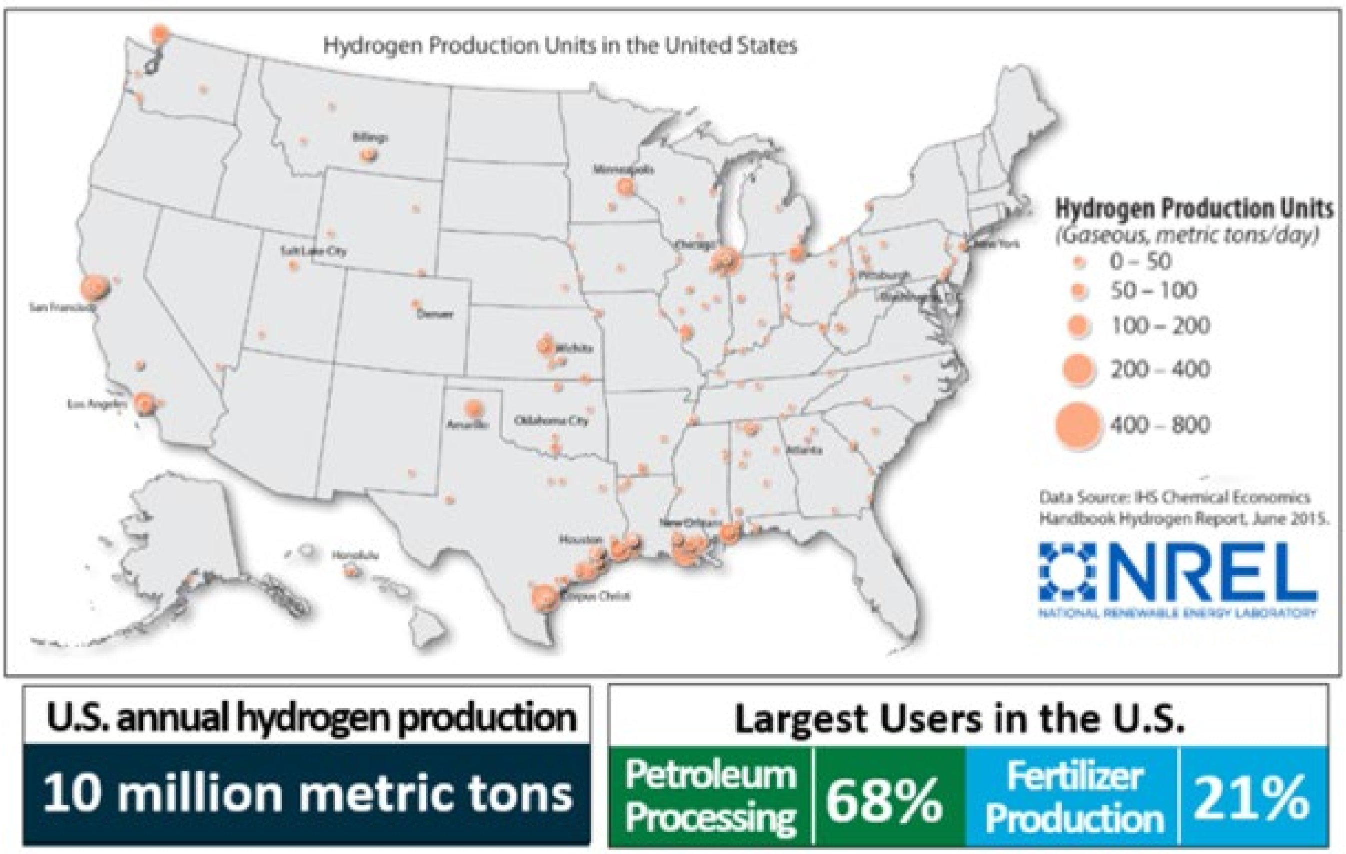
[11] https://www.t2mglobal.com/technology

- Carbon credits are not available for clean energy projects that make use of stranded resources produced through non-green methods.
- AES is such a case where wasted H_2 may be recycled with no incremental CO_2 emission production. CARB approval is needed to modify the policy to include electricity generated from wasted resources as renewable energy.

Outreach to Legislature and Policymakers for Policy

T2M identified an important opportunity for CEC and California state agencies for the Green Hydrogen definition. This was provided in the survey as follows: "Hydrogen from waste syngas needs to be defined as Green in the Legislature for future investment to benefit California stakeholders."

Figure 40. Major Hydrogen Producers and Users in the U.S.



About 25% of H_2 produced is underutilized/wasted – is it green?

Source: NREL Storage Futures Study and T2M Global for AES.

Importance of AES to California's Clean Energy and Climate Goals

The use of wasted resources such as diluted H_2 streams is an important opportunity in achieving California's clean energy goals while providing the energy security needed to thrive. Several ways that AES-H_2 can help California to achieve its goals include:

Carbon Footprint Reduction: Peak power management in California uses natural gas or other fossil fuels. This increases the carbon footprint of using renewables with grid support using fossil fuels. Reducing power purchased from the grid during peak demand will significantly decrease carbon footprint — a crucial step toward carbon-neutral production.

Energy Security for Mission-Critical Facilities: LDES plays an important role in enhancing energy security for mission critical facilities. LDES uses cheaper electricity to produce on-site dispatchable power when electricity is in short supply and expensive. This reduces the cost of electricity to the host site while firming up the electricity supply. Electricity from AES-H_2 can also be used to power a facility's critical bus to maintain essential operations during a grid power outage. This has the potential to reduce or eliminate the need for highly polluting, noisy, and maintenance-intensive diesel backup generators.

Firming Up Intermittent Renewable Power (Wind and Solar): AES has the ability to support the intermittency of solar and wind, as well as provide resiliency against natural disasters. Rapid load variations typical of wind and solar power production can be compensated for by the fast response of AES-H2 LDES. It stores excess renewable power in the form of H_2. It returns the stored power to the grid using a fuel cell when renewable generation is insufficient to meet demand.

- The need to firm up renewable power is growing exponentially. It is causing serious concerns for grid stability. It has created an increased need for grid support services.
- As illustrated in **Figure 1** earlier, the monthly curtailment of renewables in the last 3 years increased from approximately 50 GWh to over 500 GWh.
- Using AES experimental data above (10 MWh/ton of H_2) the curtailed electricity of 500 GWh/month can produce 500,000 tons of H_2 per month.
- At $5/kg H_2 price, 500,000 tons of H_2 is worth $2.5 billion/month of new revenue.
- At 90 percent round-trip efficiency, AES-H_2 can provide 450 GWh/month of grid support during evening shortages.
- This is an excellent opportunity for LDES to firm up renewable power while reducing associated GHG emissions.
- In the stretch case where the advanced electrolyzer can address 100 percent of curtailed renewables (3.33 GWh/day), more than 7 TWh of electricity can be stored and saved yearly with cost savings of over $2 billion for California. Using a GHG emission factor of 0.331 kg/kWh carbon dioxide equivalent (CO_2e), this would lead to savings of approximately 2.66 M tons CO_2e per year.
- Ultra-Low Emission Signature - The system emissions for criteria pollutants are nearly zero (no nitrogen oxides [NOx], sulfur oxides [SOx], etc.).
- Benefits to disadvantaged communities: The value-added use of waste forestry biomass for renewable hydrogen production can help reduce prevalent forest fire risks and offers economic opportunities and a healthier environment.
- Ratepayer electricity cost savings - More than $1.2 billion/year of savings from excess renewables.

- IOU savings in curtailment – more than $300 million/year not paid to the neighboring states.
- GHG emission reduction of ~2.66M tons CO_2e/year to meet California mandates.
- Economic benefits to disadvantaged communities: Creation of more than 2,000 jobs per year in California.
- Energy storage as e-H_2 (greater than20 GWh/day) contributes to California's 100 percent clean electricity goal by 2045.

CHAPTER 4: Conclusion

All goals and objectives for the electrolytic hydrogen energy storage project have been successfully accomplished or exceeded. The highly promising results open a new cost-competitive pathway to meet California's urgent needs for LDES to retain the value of its excess renewable electricity. Technology scale-up and demonstration steps are highly warranted to advance SB 1369 goals from research to reality as highlighted below.

- Estimated benefits to California stakeholders, IOUs, disadvantaged communities, low-income communities, and EJ communities and performed outreach activities.
- Met and exceeded the target of 80 percent efficiency for energy storage.
- Reduced electricity consumption by 80 percent compared to water electrolyzers.
- Operated AES under a variety of market conditions for over 2,000 hours.
- Successfully scaled up and validated AES by 25 times, from less than 0.2 to 5 kg/day.
- Developed 100 kW-class energy storage building block for California microgrid support.
- Surveyed over a dozen California sites as early adopters for deployment.
- Estimates show dilute/waste hydrogen streams have a cumulative potential of over 20,000 GWh/year energy storage for AES to support California needs.
- Validated AES potential to produce H_2 at less than $4/kg at scale.
- Identified pathway to a LCOS of less than 5 cents/kWh.
- Used guidance from TAC and IOUs to identify early adopters for AES-H_2 storage.
- Increased AES technical readiness level from four to six.

Potential Benefits to California Ratepayers

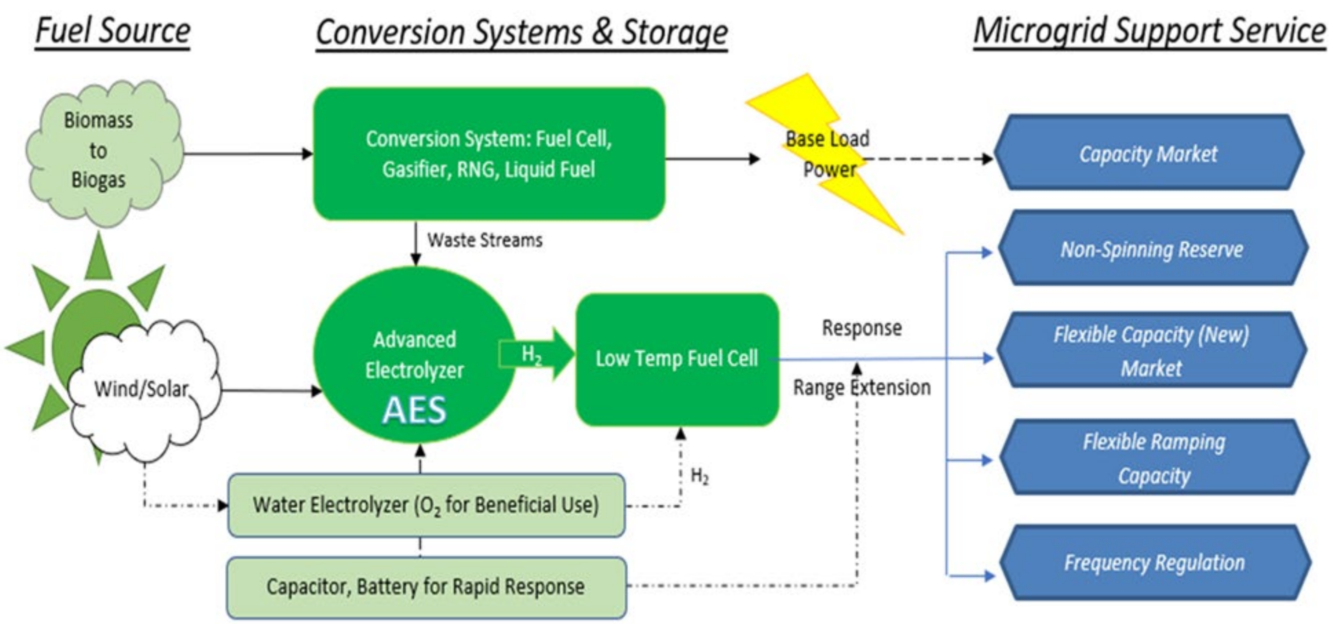
- The curtailment savings are estimated to exceed $1.2 billion/year to ratepayers.
- More than $300 million/year curtailment savings to IOUs by eliminating payments to other states and purchase of expensive electricity during shortages in evenings.
- The reduced use of fossil fuels for managing peak demand is expected to reduce GHG emissions by 2.66 metric tons/year.
- The deployment of AES-H_2 in higher priority communities will create over 2,000 well-paying jobs and improve quality of life due to healthier environments.

Path Forward and Demonstration Readiness

The AES technology will accelerate the momentum to meet California's 2045 clean energy goals by acting as a range extender for the conventional battery storage. The technology is ready for pilot scale demonstration to validate the following advantages over existing energy storage systems such as lithium-ion batteries:

- LDES with negligible self-discharge: weeks and months.
- Demand following capabilities: Store excess electricity, provide on-demand power.
- Higher round-trip efficiency with a goal of exceeding 90 percent.
- Reduced maintenance and operating costs: LCOS of less than 5 cents/kWh.
- Longer system life: Demonstrate one year of operation.
- Ease of integration in microgrids: Demonstrate behind the meter and grid support benefits as shown in **Figure 41**.

Figure 41. Electrolytic Hydrogen Storage for Grid Support Services



Enabler technology for customer side of the meter applications.

Source: T2M Global

GLOSSARY AND LIST OF ACRONYMS

Term	Definition
AC	Alternating Current
AES	Advanced Electrolyzer System
BOP	Balance of Plant
BTU	British Thermal Unit (1 kWh = 3413 BTU)
California ISO	California Independent System Operator
CapEx	Capital Expenditure
CARB	California Air Resources Board
CEC	California Energy Commission
CHBC	California Hydrogen Business Council
cm^2	Square centimeter
CO	Carbon monoxide
CO_2	Carbon dioxide
CO_2e	Carbon dioxide equivalent
CPUC	California Public Utilities Commission
DC	Direct current
DOD	Department of Defense
DOE	Department of Energy
e-H_2	Electrolytic Hydrogen
E-BOP	Electrical Balance of Plant
EJ	Environmental Justice
EPIC	Electric Program Investment Charge
EPRI	Electric Power Research Institute
EV	Electric vehicle
GHG	Greenhouse gas(es)
GWh	Gigawatt hour
H_2	Hydrogen
H_2O	Water
IOU	Investor-Owned Utility
kg	Kilogram
kW	Kilowatt
kWh	Kilowatt hour

Term	Definition
LCOE	Levelized Cost of Energy
LCOS	Levelized Cost of Storage
LDES	Long Duration Energy Storage
LFG	Landfill gas
mA	Milli-ampere
M&V	Measurement and Verification
M-BOP	Mechanical Balance of Plant
MBTU	Million British Thermal Units
MW	Megawatt
MWh	Megawatt hour
N_2	Nitrogen
NREL	National Renewable Energy Laboratory
O_2	Oxygen
OpEx	Operating expenses
PG&E	Pacific Gas and Electric
PSA	Pressure swing absorption
psi	Pounds per square inch
PV	Photovoltaic
R&D	Research and Development
RNG	Renewable Natural Gas
SMR	Steam methane reforming
Syngas	Synthesis gas
T2M	T2M Global, LLC
TAC	Technical Advisory Committee
TWh	Terawatt hour
W	Watt

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Project Deliverables

- Critical Project Review Reports #1 and#2
- Progress Reports
- Measurement and Verification Plan
- Measurement and Verification Report
- AES Test Report
- Operation and Performance Evaluation Report
- Kick-off Meeting Benefits Questionnaire
- Mid-term Benefits Questionnaire
- Final Meeting Benefits Questionnaire
- Final Project Fact Sheet
- Conceptual Commercial Scale AES System Design Report
- Final Technology/Knowledge Transfer Report
- Final Production Readiness Plan
- Final Report

Project deliverables, including interim project reports, are available upon request by submitting an email to pubs@energy.ca.gov.

ENERGY RESEARCH AND DEVELOPMENT DIVISION

Appendix A: Press Release for CHBC for Membership

February 2024 | CEC-500-2024-008

APPENDIX A:
Press Release for CHBC for Membership

Figure A-1. Outreach to Emerging H2 Industry for AES

T2M Global President Pinakin Patel Elected to California Hydrogen Business Council Board

Pinakin Patel **T2M Global** **CALIFORNIA HYDROGEN BUSINESS COUNCIL**

Director at Large

Hydrogen Means Business in California!

Director at Large
President
T2M Global

Pinakin Patel is President of T2M Global, which provides strategic guidance for Tech2Market and commercialization. Pinakin specializes in consulting and project development for "Waste to higher value" co-products: system integration for waste heat recovery via thermal integration, low-level waste heat to power technologies, pyrolysis, syngas, Tri-gen engine, and strategic alliance for project development and funding. Development of advanced technologies for hybrid systems for low-cost and high efficiency applications, fuel cells and hydrogen infrastructure. Currently managing several projects developing novel technologies in support of H2 infrastructure development.

He previously worked for four decades at FuelCell Energy as the Director, Advanced Technologies and holds over thirty patents in fuel cell and hydrogen technologies.

T2M President elected to prestigious CHBC Board position.

Source: T2M Global

CALIFORNIA ENERGY COMMISSION

CALIFORNIA NATURAL RESOURCES AGENCY

ENERGY RESEARCH AND DEVELOPMENT DIVISION

Appendix B: Project Fact Sheet

February 2024 | CEC-500-2024-008

APPENDIX B:
Project Fact Sheet

Figure B-1: Project Fact Sheet Page 1

T2M Global

Project Fact Sheet: Advanced Oxygen-free Electrolyzer (AES)

Ultra-high Efficiency, Lower-Cost, Green Electrolytic Hydrogen for California

Critical Needs: California urgently needs long-duration storage solutions to retain the value of its excess renewable electricity. Over 100 GWh of electricity storage is needed to support the grid during the evening ramp. Batteries are suitable only for short-duration storage. H_2 is needed for long-duration storage (SB1369). Dilute hydrogen streams and waste heat are stranded assets, that lead to harmful emissions and cost additional resources for disposal.

The Solution: T2M Global has successfully demonstrated "proof of concept" for a Green Electrolytic H_2 Energy Storage using Advanced Electrolyzer System (AES) for grid support. It offers superior efficiency for storage compared to conventional batteries (**Figure 1).** It is attractive for deployment in disadvantaged communities. The AES, a solid-state device with fewer moving parts, has lower maintenance costs and promises a dramatic reduction in hydrogen production costs: <$4/kg H_2 in the near term, <$2/kg long-term.

The waste H_2 streams in California have a potential to produce 200,000 ton/yr H_2 using AES and excess electricity (**Figure 2**). AES has been successfully validated on a variety of waste H_2 streams, as shown in **Table 1**. A conceptual design for 100 kg/day H_2 (100-kW class) AES Building Block has been developed. The AES-H_2 energy storage system is an enabler for DC microgrids - a unique opportunity for data centers and military applications. The multi-purpose AES technology leverages California's technology investments in hydrogen, biomass gasifiers operating on forestry and agricultural wastes, and fuel cells.

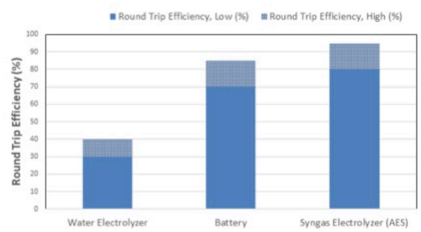

Figure 1. Competitive Landscape for H_2 Energy Storage:
AES offers superior efficiency compared to conventional batteries.

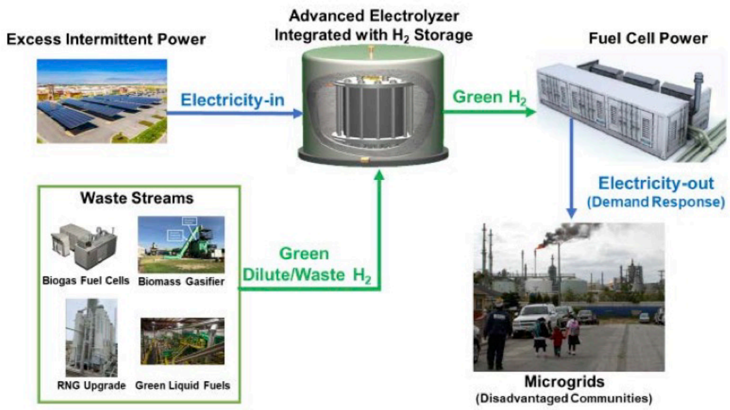

Figure 2. Advanced Electrolyzer for Long Duration Energy Storage: Produces green hydrogen from excess electricity and waste H_2 streams.

Project Innovation, Accomplishments and Advantages: The AES technology utilizes O_2-free H_2 carrier for greater safety, easier permitting and up to 50% lower CapEx. Major accomplishments in the AES-H_2 project, as illustrated in **Table 1**, met/exceeded all stretch goals. The intermittency of renewables is counterbalanced by adjusting the operating current density to absorb excess electricity by producing additional H_2.

Page 1 of 2

Source: T2M Global

Figure B-2: Project Fact Sheet Page 2

Table 1. Major Accomplishments to Benefit CA Stakeholders:
Highly encouraging pathway for lower-cost renewable hydrogen.

Performance Metric	Performance Targets			Status	Accomplishment
	Benchmark	Minimum	Goal		
Electricity Use (kWh/kg)	50-70	15	10	10	Met stretch goal
H_2 Production Rate (mA/cm^2)	200	300	400	400	Met stretch goal
Round-trip electrical efficiency (%)	25-36	60	80	>80	Exceeded stretch goal
H_2 Recovery from Syngas (%)	N/A	70	80	80	Met stretch goal
Feedstock Flexibility (%H_2 in syngas)	N/A	20	10	10	Met stretch goal

The AES-H_2 technology offers the following beneficial features:

- **Ultra-high Electrical Efficiency:** The AES-H_2 dramatically reduces electricity use by 80% compared to conventional electrolyzers, producing lower-cost H_2 at <$4/kg.
- **Enhanced Safety at Lower Cost:** Oxygen-free electrolysis reduces fire and safety hazards.
- **Rapid Response and Range Extension:** Suitable for long-duration energy storage.
- **Feedstock Flexibility for Greater Deployment:** AES can operate on a variety of dilute/waste hydrogen streams, which is attractive for deployment in multiple market segments.
- **Modular Design for Rapid Deployment:** Design for manufacturing, ultra-compact footprint for rapid and low-cost installation, easier maintenance due to fewer moving parts.

Anticipated Benefits to California: The AES - Fuel Cell hybrid storage system is uniquely suitable for behind the meter applications. It is suitable for both residential and industrial customers, who are looking for lower cost and greater sustainability. The AES Module can utilize dilute hydrogen from syngas, biogas and/or RNG without ANY adverse environmental emissions. The lower cost electricity storage solution will help keep the electricity rates low, support EV charging and increase penetration of renewables.

Ultra-Low Emission Signature - The system emissions for criteria pollutants are nearly zero (no NO_x, SO_x, PM, etc.). The GHG emissions are also nil when waste-derived biogas is used as the feedstock to produce hydrogen. It will help California meet ambitious environmental targets.

Water Independent Power - The AES technology is entirely water-independent (unlike water electrolysis that requires large quantities of purified water – up to 20 tons of water per ton of H_2). The fuel cell for electricity-out can export product water for draught-prone California.

On-site Demand-response Capability – A 1 ton/day AES Module can provide on-demand dispatchable 1 MW power and over 20 MWh of electricity storage to support community energy needs. This is very critical during the evening ramp in California, where EV charging load is growing rapidly and there is no power from solar PV. The modular design makes capacity additions easier at lower costs - very desirable for microgrids growth planning.

Enhanced Quality of Life for Disadvantaged Communities (DACs): The value-added use of waste forestry biomass to biogas provides a source of renewable hydrogen, and also helps lower forest fire risks prevalent in DACs. The availability of hydrogen in these communities offers them an opportunity to refuel fuel cell vehicles (cars, buses and vocational vehicles) and to support microgrids for a healthier environment and enhanced economic opportunities.

Contact:
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Source: T2M Global