Final Technical Report

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Project Title: Advanced Oxygen-Free Electrolyzer for Ultra-Low-Cost H_2 Storage for Fossil Plants

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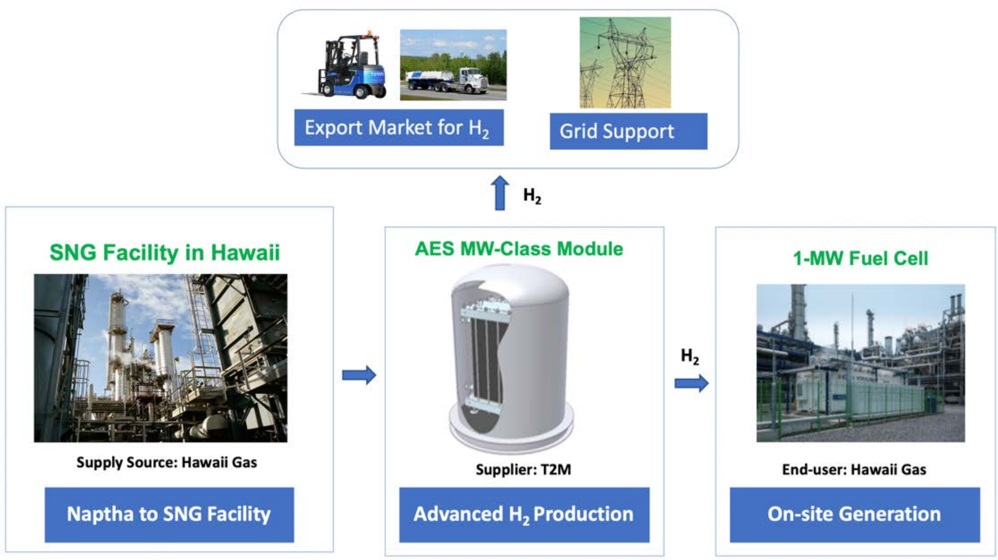

Figure 1. Lower Cost H_2 from Stranded Resources:

The dilute syngas from SNG plant will be upgraded to higher value products.

Source: T2M Global

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Abstract

DOE's Office of Fossil Energy and Carbon Management has determined that long-duration energy storage solutions co-located with fossil energy assets offer significant benefits to the fossil industry, electric utilities, and customers. T2M Global has developed an Advanced O_2-Free Electrolyzer System (AES) Technology for low-cost, long-duration H_2 energy storage for fossil plants. The MW-class AES Module conceptual design aims to upgrade stranded assets (dilute/waste syngas streams, excess electricity, and waste heat) at fossil plants to higher value H_2 for additional revenue and greater sustainability. The H_2 energy storage equips fossil plants with the load following capability needed for the lucrative grid-support services market created by Variable Renewable Energy (VRE) resources. Hawaii Gas, the owner of a Naphtha-to-Synthetic Natural Gas (SNG) fossil plant, has potential to produce up to 1.7 tons of H_2 per day for beneficial uses. This H_2 can make Hawaii Gas self-sufficient and eliminate external power purchases. It can also provide dispatchable zero-carbon power on-demand for additional revenue, while providing benefits of decarbonization. The revenue benefits to Hawaii Gas are estimated between \$5 million to \$10 million depending on the plant operational scenario. The Hawaii Gas site offers DOE the unique benefit of technology demonstration for industrial decarbonization while improving its competitive position.

The AES technology developed by T2M is a safer, more efficient, and inexpensive alternative to conventional water electrolysis. The experimental results indicate that MW-class Advanced Electrolyzer Systems could achieve a round-trip efficiency for electricity storage of more than 80%. By comparison, conventional water electrolyzer systems have a round-trip efficiency closer to 40%. This dramatic increase in electrical efficiency was accomplished by eliminating high parasitic losses associated with co-production of O_2 in conventional water electrolysis. Eliminating O_2 leads to lower capital cost and greater durability.

All project goals for H_2 energy storage have been met or exceeded. A design for a 100-kW-class AES building block has been developed leading to a MW-class module for larger energy storage systems. Results show that the AES technology has the potential to outperform lithium-ion batteries, especially in long duration energy storage applications. The AES' enhanced safety features and flexibility to integrate with a variety of stranded resources makes AES technology especially suitable for deployment in disadvantaged communities to advance US DOE goals for Diversity, Equity, and Inclusion (DEI). The recommendation for the next steps includes scaleup and demonstration of this highly promising AES technology at a fossil plant site. Hawaii Gas is very interested in hosting a demonstration for H_2 energy storage and validating AES benefits to fossil plants.

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The T2M Global team would like to thank the DOE Office of Fossil Energy and Carbon Management for the support of this project, as well as the Project Manager, Mr. Jason Hissam, for their valuable and thoughtful guidance throughout the duration of the project. Special thanks are due to Hawaii Gas and their technical team for their valuable support in plant operation data and review of AES value proposition opportunities. The team would also like to thank their Technical Advisory Committee members for their valuable insight to develop a market-responsive product and deployment strategy for early adopters. Additionally, the team would like to thank their project partners and vendors for their contributions towards the successful H_2 energy storage technology validation.

Summary:

Overview of AES Energy Storage System:

The T2M Team has developed and validated an O_2-free Advanced Electrolyzer for H_2 based Energy Storage Systems. It has ultra-high electrical efficiency at competitive costs to make fossil power plants load-following and enhance their value proposition. The Advanced Electrolyzer System (AES) targets to double the round-trip electrical efficiency of conventional water electrolyzer systems (from < 40% to > 80%), while reducing their capital cost by ~50%. 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 Advanced O_2-free Electrolyzer Technology for low-cost, long-duration H_2 energy storage for fossil plants (**Figure 2**). This will upgrade stranded assets at fossil plants (waste/dilute syngas streams, waste heat and excess electricity) to higher value H_2 and on-demand, dispatchable, zero-carbon power. AES enhanced safety features make it especially suitable for disadvantaged communities to create value from wasted resources while providing healthier environments and economic opportunities.

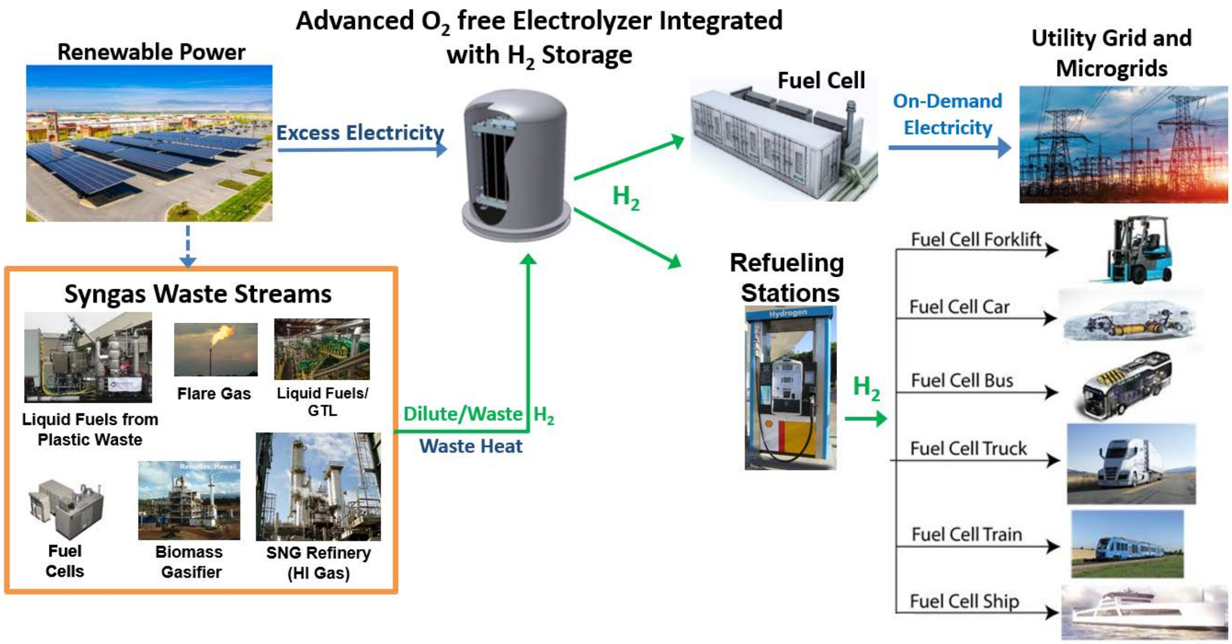


Figure 2. Produce Higher Value H_2 from Dilute Syngas Streams:

Extend the life of Fossil Plants – Support variable renewable energy.

Source: T2M Global

The AES technology will accelerate the momentum to meet the nation's ambitious decarbonization goals, including by acting as a range extender for conventional battery storage and to support variable renewable energy (VRE) systems. The AES advanced O_2-free electrolyzer for ultra-low-cost hydrogen energy storage systems provides significant advantages for fossil plants over existing energy storage systems such as battery, pumped hydro, thermal, and mechanical energy storage systems, including:

- Long duration energy storage with negligible self-discharge.
- Feedstock flexibility.
- Load following capabilities.
- Higher round-trip efficiency.
- Reduced maintenance and operating costs.
- Longer system life.
- Ease of integration in microgrids.

The program target of >80% round trip efficiency has been met as illustrated in **Figure 3**. The round-trip efficiency for energy storage for AES is compared with the conventional water electrolyzer and the conventional battery. As expected, the water electrolyzer energy consumption ranges from 40-70 kWh/kg. T2M's laboratory tests for AES showed an energy consumption of 5 to 15 kWh/kg. This is about 80% lower than conventional water electrolyzers. This contributes to the greatest round-trip efficiency for energy storage, as shown in **Figure 3**, resulting in an estimated H_2 production cost of <$4/kg. 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.

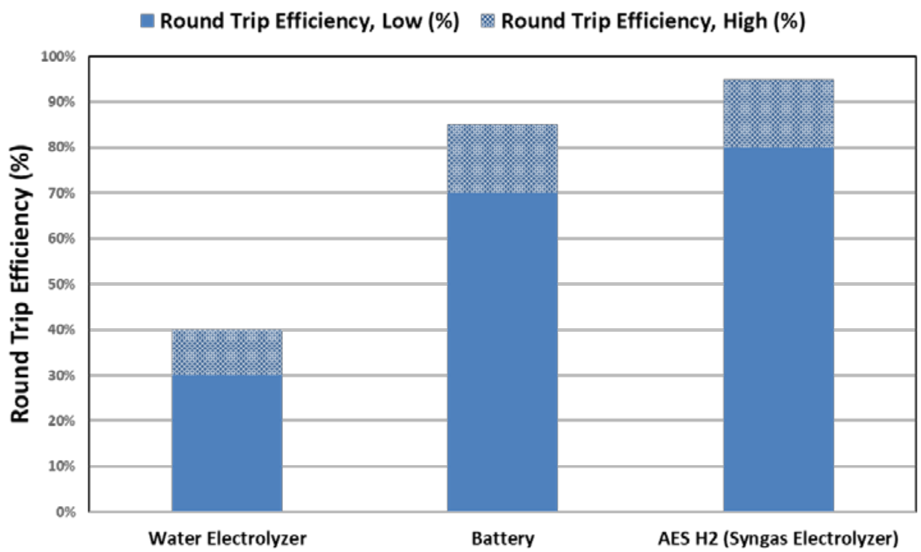


Figure 3. More than Doubles the Efficiency of Water Electrolyzer:
AES demonstrated the highest electrical efficiency: >90%.

Source: T2M Global

Benefits of AES Integration with Fossil Assets

AES has significant potential to enhance the value proposition of fossil plants by producing high value H_2 from stranded resources. Hawaii Gas has 8-12% H_2 in its product SNG stream, among the highest in the nation. Currently there is no commercially available technology to capture this high value H_2. Implementing AES technology will help utilize the currently wasted H_2. It can recover up to 80% of H_2 at an attractive energy consumption (<15 kWh/kg). These benefits of AES translate to significant savings for fossil plants producing SNG with H_2 as a diluent, improve resiliency with H_2 energy storage for on-demand power, as well as providing additional revenue from recovered H_2, **Figure 4**.

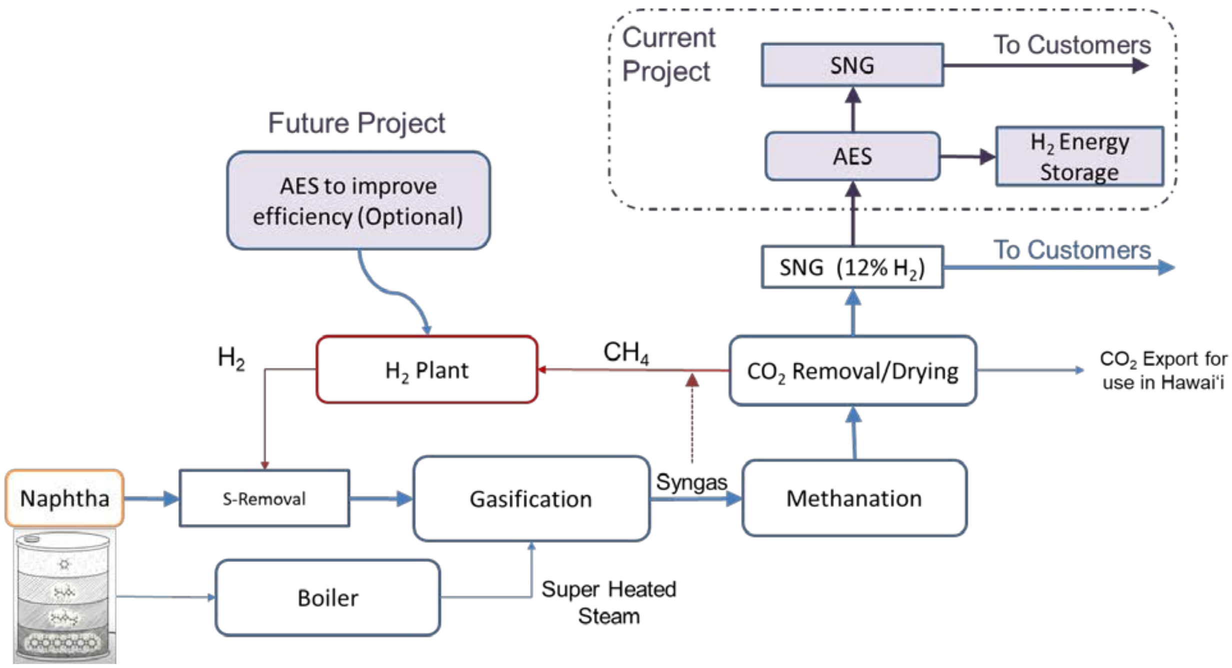


Figure 4. AES Beneficial Integration with Hawaii Gas SNG Plant:

Additional future benefit with AES integration with H_2 production plant.

Source: T2M Global

Benefits of On-demand Electricity: The life of fossil plants decreases when operated at a variable load. AES Modules render the Fossil Plants to become load-following by converting the excess electricity to pressurized H_2, which can later be used to generate dispatchable power when it is the most valuable. AES technology will help to open a multi-billion-dollar market for fossil power plants by creating value from their currently stranded assets: excess electricity, waste heat and dilute H_2 streams. Thus, AES will accelerate the national momentum for cleaner energy goals, especially by acting as a range extender for fossil power plants to support the utility grid challenged with Variable Renewable Energy.

AES provides fossil power plants the much-needed load following capability and opportunity for enhanced cashflow from grid support services as illustrated in **Figure 5**. Hydrogen storage will bring additional revenue from ancillary services like Frequency Regulation, Flexible Capacity, Reactive Power for Power Factor Correction, Load Ramp-Up and Ramp-Down in kW/sec or kW/min, etc. AES provides safer operation of critical equipment, and hence, a lower maintenance cost for the fossil plant by eliminating load cycling and thermal cycling. AES will extend the useful life of fossil plants by reducing overall GHG emissions, and thus, reducing their exposure to potential carbon taxes. Oxygen-free AES is inherently safer than water electrolyzers. It is more cost effective and suitable for long duration energy storage. The modular design of AES provides a smaller footprint, inexpensive installation, and easier capacity addition. Hawaii Gas provided guidance for the integration of AES in their fossil assets to develop the deployment strategy. The T2M Team has estimated the potentially stranded assets in coal, pet-coke, naphtha, natural gas and other fossil-fueled plants to produce H_2 for grid support for additional revenue.

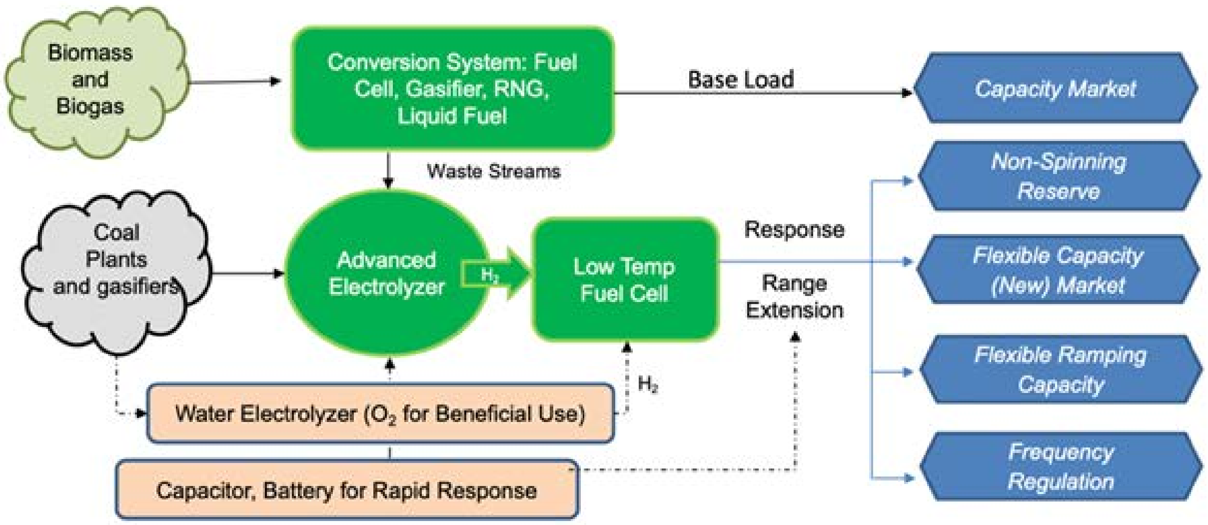


Figure 5. Load Following for Fossil Power Plants:

Over $4 Billion in potential revenue from Grid Support Services.

Source: T2M Global

Energy Storage - Battery vs. Hydrogen:

Batteries are suitable for short-duration energy storage but become prohibitively expensive for long-durations, **Figure 6**[1]. For short duration battery storage (< 8 hours), the levelized cost of energy (LCOE) is estimated at $90-$100/MWh. For 24 hours of storage, the LCOE doubles to >$200/MWh. For longer durations of 30 days, the battery LCOE increases to an astounding $5,000/MWh, prohibitively expensive for 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 MM[2].

[1] Source: https://www.ethree.com/publication/

[2] Source: https://www.tesla.com/megapack/design

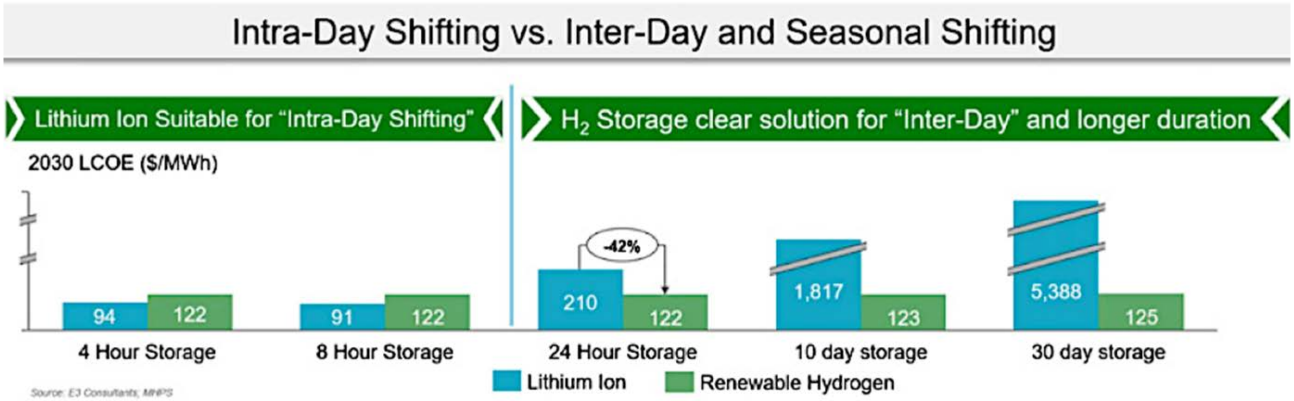


Figure 6. Competitive Landscape - Battery vs Conventional H_2:

Battery for short duration, H_2 for long duration energy storage.

Source: E3 Consultants, H_2 from Water Electrolysis vs. Battery

The LCOE for conventional H_2 using water electrolysis is estimated by E3 Consultants to be $125/MWh. The technoeconomic analyses for AES promise an LCOE of $50/MWh. The 700 GWh/month of curtailed electricity could be used to produce 70,000 tons of H_2 using AES, which, at $5000/ton, has a value of $350 MM. An additional advantage of AES technology is its low energy consumption versus H_2 produced from water electrolyzers and pressure swing absorbers.

Introduction

Project Team and Stakeholders

The H_2 storage for fossil plants project was managed by T2M Global as the prime recipient. T2M Global has over 300-years of cumulative relevant experience in advanced electrolyzer development, scale up from 40 cm^2 to 1000 cm^2 cell area, and operation on dilute syngas from natural gas/digester gas fuel cell plants (co-sponsored by NETL) to produce hydrogen for energy storage. President of T2M Global, Mr. Pinakin Patel, 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, CFO of T2M Global, for financial modeling and reporting. The project management included reporting, outreach to stakeholders, and coordinating the efforts of T2M's staff, subcontractors, advisors, and vendors.

Project partner and Fossil asset owner and operator, Hawaii Gas, provided valuable site-specific data and technical support to guide market-responsive AES hydrogen energy storage system development including the MW-class Module for future deployment at their site. They are very interested in hydrogen energy storage for decarbonization and to produce load-following power while creating additional revenue streams from grid support services by using this hydrogen. They have a Naphtha to SNG plant operating in

Hawaii with stranded dilute hydrogen in their product SNG and other syngas streams. Hawaii electric rates are among the highest in the USA ($200-400/MWh). On-site power from AES hydrogen energy storage can bring Hawaii Gas multi-million dollars in annual savings while reducing their GHG emissions.

The project's Technical Advisory Committee (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 US-DOE and US-DoD for successfully developing advanced H_2 and fuel cell technologies. This experience has helped T2M in AES scaleup, validation and integrated building block design for H_2 energy storage for fossil plant deployment.

T2M's team included subcontractors who were instrumental in developing key components of the AES stack and balance of plant (BOP) components of the ultra-low cost AES H_2 energy storage system. 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 cumulative experience in the area of biogas upgrading equipment, pressure vessels, design and fabrication of modular systems for fuel cells and electrolyzers. They supported design, fabrication, and delivery of key components for AES testing.

Technology Options for H_2 Energy Storage:

The T2M team evaluated conventional water electrolyzer versus Advanced Electrolyzer (syngas electrolyzer) for their performance, efficiency, and capital cost. The results are summarized below.

Conventional Water Electrolysis: It is the current method to produce H_2 using electricity. Worldwide, its popularity is growing as a result of the transition to a zero-emission economy. Water electrolysis and the associated electrochemical reaction involves using DC electric current to split H_2O into its constituents, H_2 and O_2, at two separate electrodes. This conventional H_2 production technology suffers from a number of challenges that make it unattractive for energy storage:

- Water Electrolyzers are 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 $3MM/MW, making it economically challenging for H_2 storage for fossil plants.

- 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 areas.
- Stranded Resource: Co-product O_2 is virtually wasted.
- 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 O_2 are produced, imposing safety challenges. The large volumes of pressurized hydrogen and oxygen co-products in the 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 (DAC's), which have traditionally suffered from such safety, health and fire hazards.

Advanced Electrolysis using Alternate H_2 Carriers: The high electrical consumption in water electrolyzers above is mainly due to the co-production of O_2. About 80% of the energy input to split water is utilized 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 production cost to competitive levels (<$4/kg). In addition, the O_2-free H_2 carriers offer greater safety and easier permitting. O_2-free H_2 carriers include:

- Syngas – H_2 + CO + CO_2
- Biogas, Anaerobic Digester Gas (ADG)
- Tail gases from industrial processes such as steam methane reforming (SMR), pyrolysis, semiconductor, steel manufacturing, fuel cell exhaust, etc.
- Methane – CH_4
- Ammonia – NH_3

Electrolysis of O_2-free carriers promises over 80% reduction in electricity used, **Figure 7**. This leads to significantly higher round-trip efficiency.

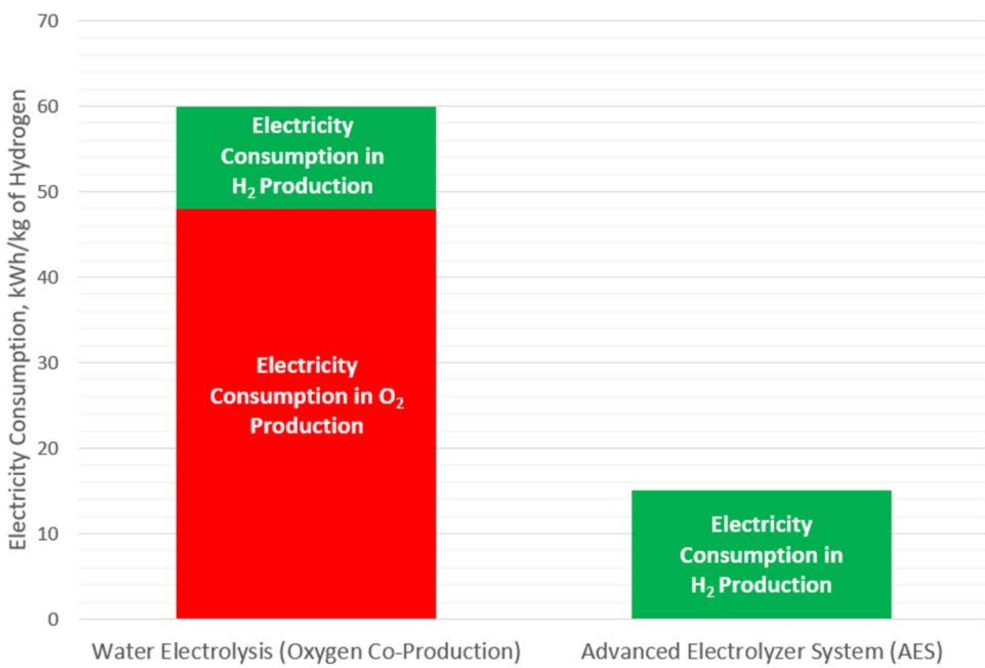


Figure 7. Competitive Landscape for Green Hydrogen Production:
AES uses 80% less electricity than water electrolyzers.

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 DAC's, as well as other market segments. **Table 1** shows a comparison of important performance metrics between AES vs. battery and conventional water electrolysis systems. A hybrid system incorporating AES 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 1. Competitive Landscape for Energy Storage Technologies:
AES technology offers higher efficiency at lower cost.

Comparable Attributes	Current	Water Electrolysis	Advanced Electrolysis (AES)	
Storage Technology	**Battery**	**Water**	**Baseline**	**Improved**
Overall Roundtrip 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
Self-Discharge (%/month)	2-5%	0.2%	0.1%	0.1%
System Life, years	10	5	15	20

Source: T2M Global

Methods, Assumptions, and Procedures

AES Project Goals

AES development began with technology scale up from kW-class level to 10-kW system, followed by its pressurization for 50% reduction in capital and operating costs. AES technology is aimed at dilute syngas streams from a variety of fossil plants. The promising validation test results at 10-kW level have been extrapolated to develop a 100 kW-class AES stack building block design and Techno-economic models for integrating with Hawaii Gas' SNG plant (Target: MW-class Module design capacity of 1-2 ton H_2 per day, up to 24 MWh energy storage, 1-MW on demand power for fossil plants). Input from the TAC and Hawaii Gas was utilized to catalog dilute syngas streams available from early adopter fossil plants to guide TEA analysis for cost-benefit estimates and commercialization plan.

The overall goals for the project and the objectives were to develop a novel Hydrogen-based Long-duration Energy Storage Module with ultra-high electrical efficiency at competitive costs, to make Fossil Power Plants load-following and enhance their value proposition. The demonstrated Advanced Oxygen-free Electrolyzer System (AES) targeted and achieved a round-trip electrical efficiency of 80%, which is double that of conventional water-electrolysis at less than 50% capital cost (Target: $1000/kW). All major goals have been successfully accomplished. Specific goals and objectives are described below:

- Develop and validate the AES energy storage system technology for electricity-in/ electricity-out applications. Advanced Electrolyzer Target: 1-10 kg of H_2/day energy storage, kW-class test vehicle with round-trip efficiency of more than 80%.
- Demonstrate feedstock flexibility by operating on different dilute/waste H_2 streams. Syngas containing 10 – 20% H_2.
- Identify dilute/waste H_2 market opportunities for energy storage.
- Improve AES for expanded markets: Streams containing CO up to 10%.
- Validate benefits of pressurized operation to reduce operating costs.
- Scale up AES technology to 10 kg/day to advance TRL level from 4 to 5.
- Develop designs for a 100 kW-class, 100 kg/day H_2 storage building block to enhance the value proposition of fossil plants by providing valuable grid-support services while reducing GHG emissions.
- Establish readiness for scale-up, prototype development, and demonstration of 100 kW-class AES building block.
- Develop AES deployment strategy in DAC's using guidance from the TAC and Hawaii Gas.

Metrics Measured

Parameters measured to validate AES performance include the following:

- Hydrogen Production Metrics:
    - Stack Voltage
    - Stack Current
    - BOP Power
    - Syngas flowrate
    - Syngas Composition
    - Hydrogen Purity
- Power Production Metrics:
    - Stack Voltage
    - Stack Current
    - Hydrogen flowrate
    - BOP Power
    - Power Produced

While there was a substantial amount of additional process information collected, these were the key measurement points used to verify the performance metrics.

Results, Accomplishments, and Discussion

All Project Milestones Met or Exceeded:

- Syngas streams available for AES integration at Hawaii Gas (Verify 1 ton/day recoverable H_2 is available) – Completed.
- Stack Operation on Selected Syngas Streams (500 hr, <15 kWh/kg) – Completed.
- Hawaii Gas review of AES integration requirements and benefits for demonstration (Target: 1 ton/day H_2) – Completed.
- Complete Baseline design for tall stack building block (Target: 100 kg/day, 2.4 MWh/day storage) – Completed.
- Prototype MW-class module design for Hawaii Gas (Target Capacity: 1 ton/day H_2, <15 MWh/ton H_2) – Completed.
- Develop a Technology Maturation Plan for MW-class module (Target: 1 ton/day H_2) – Completed.

AES Technology Validation and Durability Testing

The AES technology was scaled up 100 times, from a 100 g/day H_2 production level to 10,000 g/day 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 energy storage system, the T2M team scaled up the test facility from single cell/gram level/ambient pressure operation to multi-cell/kg level/pressurized operation system.

Increase H_2 Production Capacity: Target 10 kg/day H_2

The AES cell, stack, and system hardware were scaled up to 10 kg/day level. The team successfully produced >10 kg/day of >99.9% pure H_2 in this unit. It utilizes the following sub-systems operating in an integrated mode with emphasis on unattended operation and remote monitoring.

- Mechanical balance of plant: Feedstock supply and heat exchangers.
- Electrical balance of plant: Power supplies, UPS, fuses and breakers.
- Control system: Process instrumentation and PLC 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 DC to DC and DC to AC power controller with current and voltage regulation.
- Communications and data acquisition: Remote monitoring, data collection, alarms, event recording with internet compatibility.
- Cracker for simulated syngas production.

The simulated syngas feedstock for the AES module was generated via cracking of a hydrogen carrier, resulting in a composition by mass of ~10% H_2, balance CO + CO_2 and H_2O (steam).

The promising results from one of these test runs are shown in **Figure 8** below. The maximum production rate of 11.6 kg H_2/day was achieved at a stack current of 108 Amps, equating to a current density of 327 mA/cm^2. To achieve 10 kg H_2/day production rate, only 93 Amps of stack current was required, equating to a current density of 282 mA/cm^2. Increasing current density has the benefit of higher purity produced H_2, >99.9%, as shown in **Figure 9**. These current densities are aligned with the scaled up 100 kg/day building block design target of 300 mA/cm^2. This data was used for the 100 kW-class building block design as described later in this report.

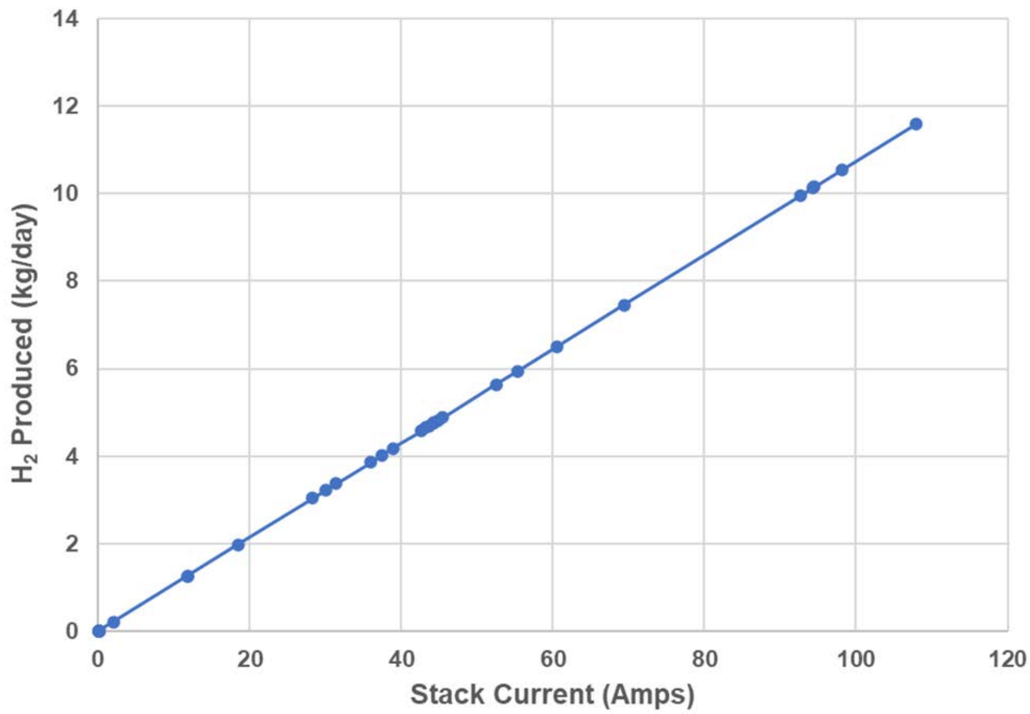


Figure 8. H_2 Production Rate Results from AES Testing:

Met and exceeded program goal of 10 kg/day H_2 with stable system operation.

Source: T2M Global

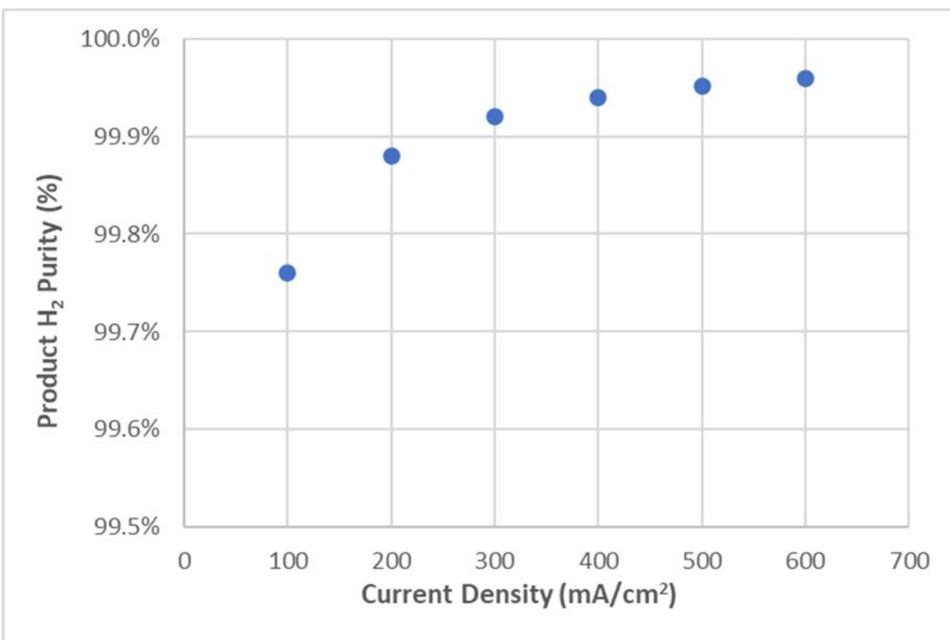


Figure 9. AES H_2 Product Purity:

H_2 purity improves with increase in H_2 production rate.

Source: T2M Global

Feedstock Flexibility Data on AES H_2 Production - AES Power Consumption:

The team tested the effects of simulated dilute H_2 waste stream compositions on AES power consumption. Surveys of syngas sources in the US identified two major diluents present in the syngas:

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

The team tested AES performance on 75 percent and 90 percent N_2 or CO_2 as diluent. AES' ultra-low energy consumption for different dilute/waste H_2 streams is shown in **Figure 10**. These results confirm that AES technology met the DOE program stretch goal of <10 kWh/kg.

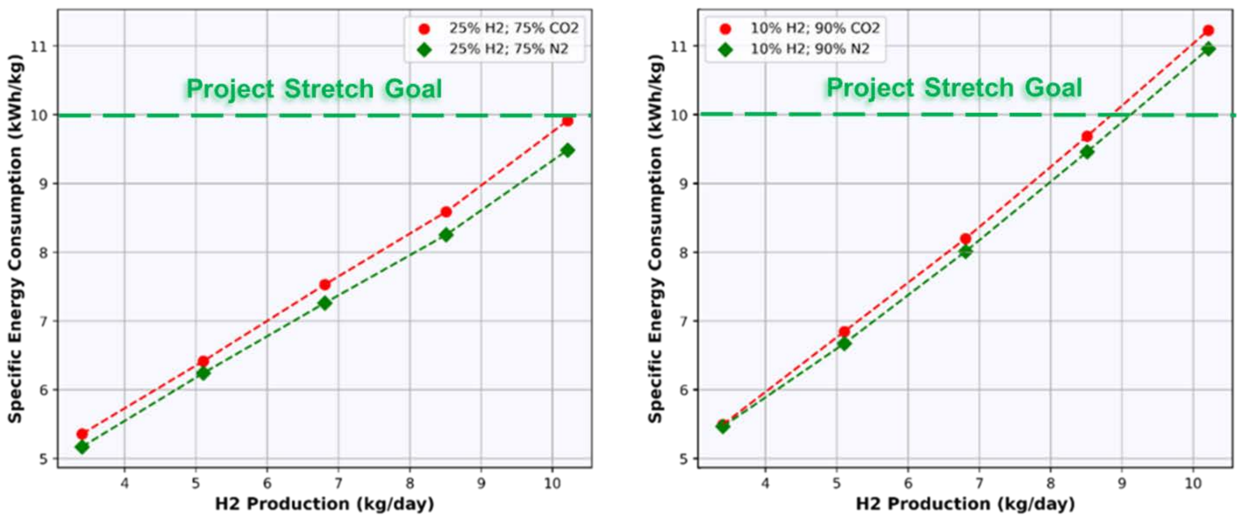


Figure 10. Feedstock Flexibility Validated - H_2 from 10% to 25%:

Met project stretch goal for electricity consumption: <10 kWh/kg H_2.

Source: T2M Global

Figure 11 compares AES power consumption for different H_2 concentrations (10 to 100%). Power consumption increases slightly as the H_2 concentration decreases. Especially at 10% H_2, the increase in power consumption becomes non-linear. **Figure 11** 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 to establish readiness for the scaleup to 100 kg H_2/day AES building block described later.

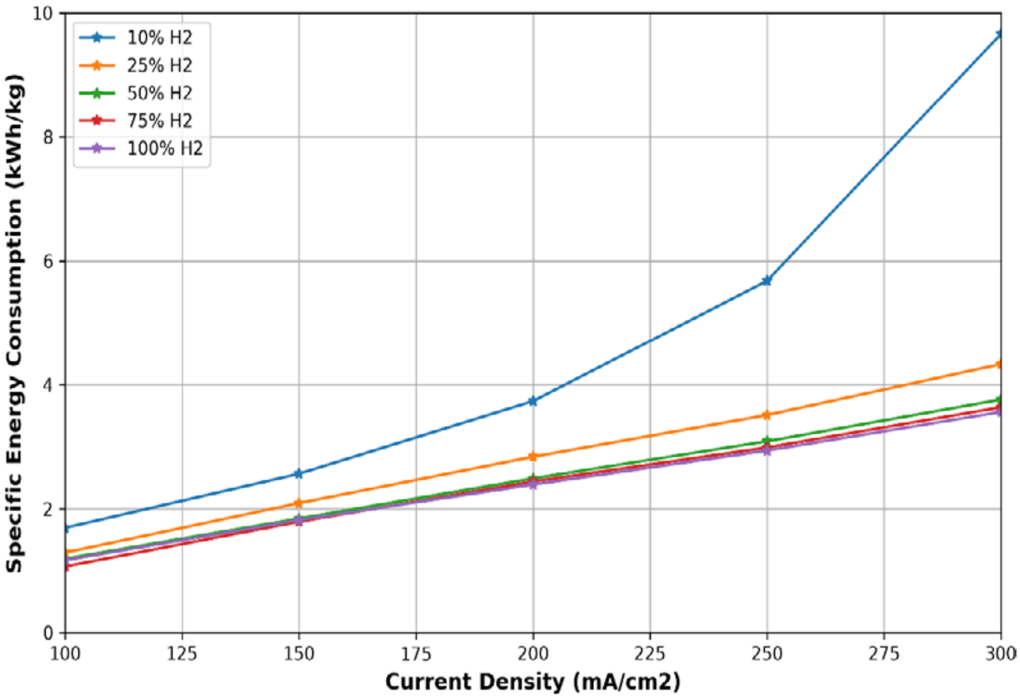


Figure 11. Effect of Dilution on AES Energy Consumption, kWh / kg of H_2:
Met program goal: For all dilutions, <10 kWh/kg H_2 specific energy consumption.

Source: T2M Global

Feedstock Flexibility - Contaminant Tolerance (e.g., Carbon Monoxide)

Some dilute/waste H_2 streams may contain 1% to 30% carbon monoxide as an impurity that may adversely impact H_2 production efficiency. There is also a concern that these impurities in the syngas, especially CO, can adversely affect the purity of the product H_2. To address this concern, an AES cell was tested with simulated dilute syngas with 11% CO as feedstock (reformate at anode in, **Figure 12**). Gas samples were taken from the anode side inlet for the feed composition and cathode side outlet for H_2 product purity and analyzed. As can be seen from **Figure 12** (left), there was no CO detected in the product H_2 (cathode outlet). This indicates excellent integrity of the electrochemical membrane used for H_2 production via advanced electrolysis. **Figure 12** (right) shows the CO concentration measured at the anode outlet compared to the anode inlet: CO concentration is reduced from 11% to 4%, indicating a corresponding increase in H_2 by 7%. The T2M team believes this beneficial feature can significantly increase H_2 production from AES operating on CO-containing dilute/waste H_2 streams. Important site-specific parameters to consider for wide deployment of AES are:

- Syngas Composition:
  - Hydrogen
  - Methane
  - Higher hydrocarbons

- Carbon Dioxide
- Nitrogen
- Water

- Syngas Pressure:
  - 1 bar, 10 bar, 20 bar, etc.
- Syngas Contaminants:
  - Carbon Monoxide: 0.5%, 1%, 10%, and higher
  - Sulfur compounds (R-S: >200 different ones)
  - Halides (R-Br, R-Cl, etc.)
  - Siloxanes

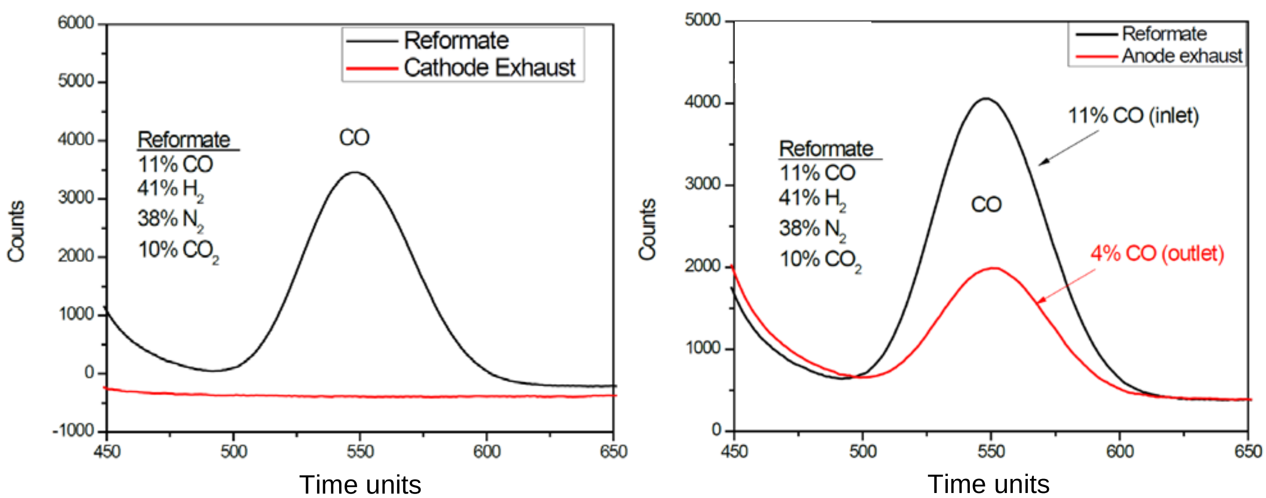


Figure 12. AES has Excellent CO Tolerance – Needed for Feedstock Flexibility:

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 AES, including:

- Increased round-trip efficiency for AES H_2 energy storage, very important for achieving the DOE's Office of Fossil Energy and Carbon Management goal for low-cost production of hydrogen from fossil fuels with zero or near zero emissions to facilitate energy storage.
- Reduced energy consumption, hence lower cost H_2.
- Increased H_2 production rate, hence lower capital cost.
- Improved compatibility with fossil plants and H_2 station storage and dispensing, reduced operating cost.

To validate the above benefits, parametric testing of AES was conducted at different operating conditions. **Figure 13** 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. **Figure 13** should be interpreted as a trade-off between capital and operating cost of the AES module: Increased pressure capability reduces the operating cost, i.e., 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.

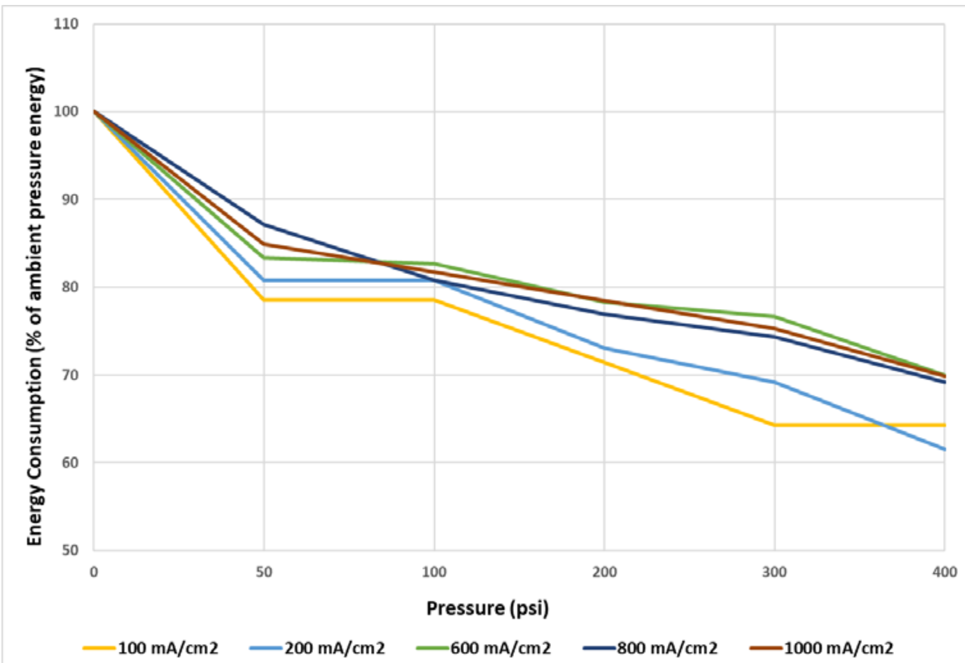


Figure 13. AES Power Consumption Decreases at Elevated Pressures:

Met the project stretch goal of <10kWh/kg H_2.

Source: T2M Global

The following are key observations that make AES for H_2 storage even more attractive with pressurization:

- The energy consumption in all these cases remained below the DOE project target of <15 kWh/kg H_2 – making it attractive for Long Duration Energy Storage (LDES) applications.
- Pressurization to 400 psi reduces specific energy consumption by ~30%.
- Pressurization enables increased H_2 production rate – from 200 to 1000 mA/cm^2.
- This translates to potential cost savings of up to 80%.

- With these attractive benefits, further scaleup of AES technology is highly warranted.

Durability Testing: 2500 Hour Operation Demonstrated

The durability testing objective was to provide performance and stability data needed for AES system design, scaleup, and technoeconomic analyses. Improvements were made to the test station for unattended operation to facilitate testing and data collection. 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 and showed excellent stability. With the highly encouraging results from this initial test, extended durability testing for 2500 hours was conducted resulting in negligible increase in specific energy consumption over the entire duration of the test.

Major observations of durability testing:

- The excellent performance stability of AES validates readiness for scaleup to 100 kg/day building block.
- The energy consumption during all durability tests remained below 10 kWh/kg, indicating potential for further reduction from the project goal of 15 kWh/kg.

Sources of Dilute/waste Hydrogen Streams: Early Adopters

The United States has an abundance of wasted resources, hundreds of millions of tons per year. **Table 2** shows some examples of dilute waste streams in the US and their energy storage potential. **Figure 14** illustrates the multiple benefits of AES recovery of H_2 from dilute syngas waste streams. Diverse feedstocks for dilute H_2 available in the near-term are:

- Dilute process streams in petrochemical and fertilizer industries:
    - Tailgas from SMR and NH_3 synthesis.
    - Gas-to-liquid using FT (Fischer-Tropsch) - recycle streams.
- Gasification/Pyrolysis Product Streams:
    - Air-blown vs. O_2-blown gasifiers: tail gas after PSA.
- Exhaust Gases from High Temperature Fuel Cells:
    - Molten carbonate
    - Solid oxide
    - Phosphoric acid
- Variable Renewable Energy – intermittency:
    - Flared gases from landfills and wastewater treatment facilities.
    - Anaerobic digester product streams and tailgas.

Table 2. H_2 from Excess Electricity → Solution for Dispatchable Power:

Nationwide potential for 200,000 GWh.

Potential Sites (Disadvantaged Communities)	Electricity Storage, GWh	
	Gross	Addressable
Electric Utilities - Wood yards	300,000	30,000
Gas Utilities (RNG, LFG), Green H_2	250,000	20,000
Municipal Wastewater - Biogas	400,000	50,000
Food Processors	350,000	40,000
Agricultural, Forestry	700,000	60,000
Total >1 Billion tons/year in US	2,000,000	200,000

Source: T2M Global

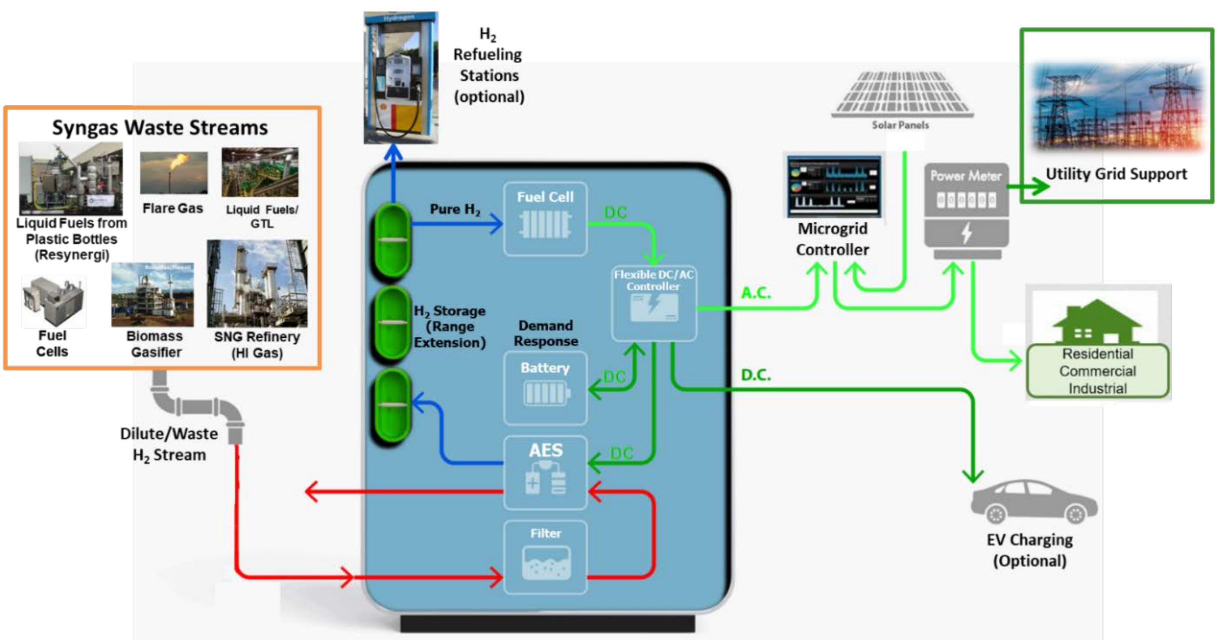


Figure 14. Syngas Waste Streams → High Value H_2 and Dispatchable Power:

AES for fossil plants - emissions reduction, competitive advantage, enhanced resiliency.

Source: T2M Global

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.

- Hawaii Gas:
    - Project partner
    - Uses naphtha feedstock to produce ~ 3 billion cubic feet/year of SNG.
    - Product SNG contains up to 15% H_2.
    - Up to 2 tons/day of H_2 can be produced utilizing AES technology.
    - **Figure 15** below shows Hawaii Gas' Naphtha to SNG plant on the left and their biogas to RNG facility on the right (first in HI), and in the middle T2M's President and project PI Pinakin Patel with representatives from Hawaii Gas, General Motors (GM), and other dignitaries celebrating Hawaii's Hydrogen Initiative.
- 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 California.
    - Medium-quality syngas: Identified 3 sites in California.
    - Low-medium quality syngas from air-blown gasifiers: Identified several sites.
- Biomass digester sites for biogas:
    - More than 20 potential sites identified: qualify for RNG incentives.
    - Municipal wastewater
    - Industrial wastewater
    - Landfill gas
- RNG and SMR sites: Hydrogen refueling stations, 6 sites identified and surveyed.
- Biogas fuel cell sites: >12 sites identified in DAC's, Low-income communities, and Environmental justice 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 grid shortages.

Figure 15. Hawaii Hydrogen Initiative in Honolulu Area:

GM & Hawaii Gas Collaboration with PI, Pinakin Patel.

Source: T2M Global

100 kg/day Building Block

Table 3 summarizes the parametric trade-off analyses performed for the below cost and risk contributing factors. The following strategy for building block design was selected:

- Near-term: Existing supply chain, 1000 cm^2 cell area
- Commercial: Alternate supply chain, 3000 cm^2 cell area

The highlighted data in **Table 3** 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.

Existing Cell Hardware: The cells in the AES stacks used in this testing were of our standard dimensions, leading to up to 5 kg/day of H_2 generation per stack. Use of this hardware would require twenty 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 not feasible for commercial production. The T2M team focused on increasing cell area using alternate supply chains.

Table 3. Increasing Tall Stack H_2 Production Capacity:

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

		Hydrogen Production Rate			
Current Density	Number of Cells	Cell Area: 200 cm^2	Cell Area: 500 cm^2	Cell Area: 1000 cm^2	Cell Area: 3000 cm^2
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
	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

Source: T2M Global

Larger Capacity Hardware: Addressing the above cost drivers requires trade-offs between larger area cell components and supply chain limitations. Larger area cells increase H_2 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, **Figure 16**, but comes with many design considerations including:
    - Increased thermal management complexity:
        - Increased stack heat generation.
        - Requires additional cooling – reducing efficiency.
        - Increases challenge of thermal management to distribute heat uniformly across each cell.
    - Adds constraints to material selections.
    - With increase in current density, tolerance management becomes more important and complex.
- Stack Height: Greater number of cells/stack is beneficial; however, component tolerance management becomes more complex as stack height increases.

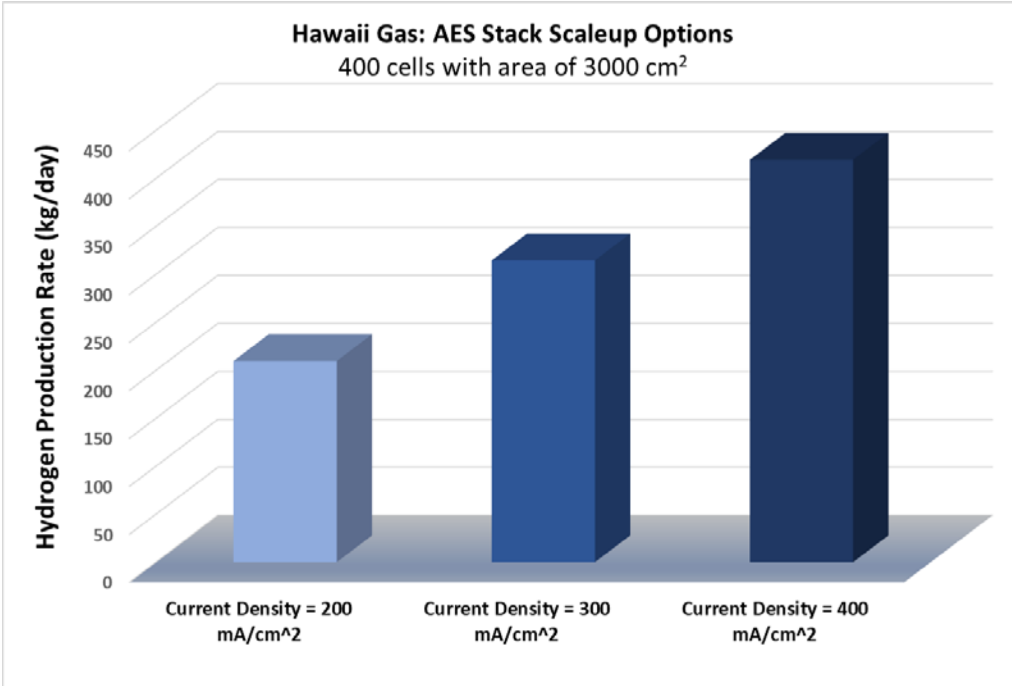


Figure 16. Higher Current Density → Beneficial → Higher Risk:

Higher current density reduces CapEx, increases cooling requirements.

Source: T2M Global

Process Flows for Baseline 1000 cm^2, 400 cells, 300 mA/cm^2: Process flowrates and velocities were calculated and analyzed for both ambient pressure operation and pressurized operation (500 psig) of AES. **Figures 17 and 18** show the results of these analyses for anode process flows at an operating pressure of 500 psig. Based on these analyses, system sizing to achieve 100 kg/day hydrogen production at ambient pressure is not practical due to the large flowrates required. The system will be designed to allow ambient pressure operation only at lower production rates for system startup and 100 kg/day H_2 production at 500 psig and dilution down to 5% H_2 concentration.

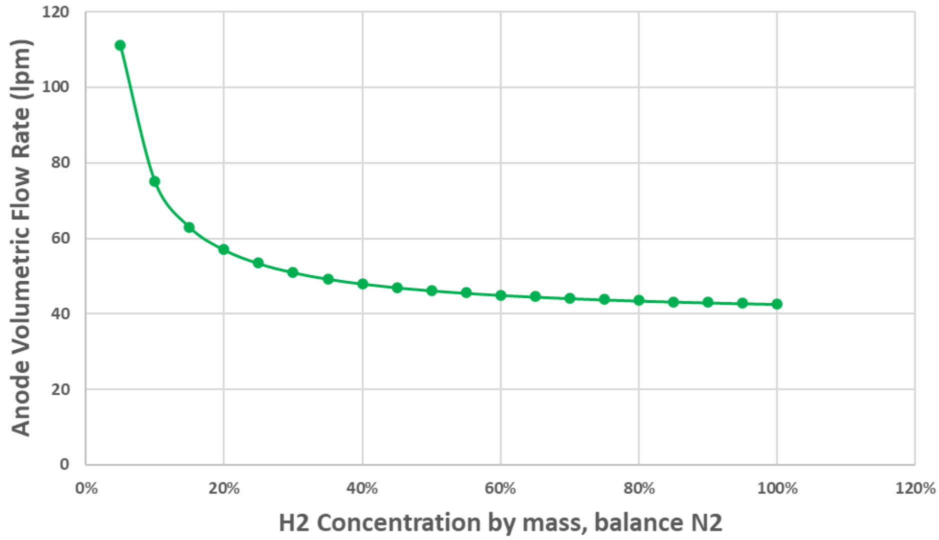


Figure 17. Effect of Hydrogen Concentration on Anode Flow Rate:
At 500 psig and 80% AES hydrogen recovery.

Source: T2M Global

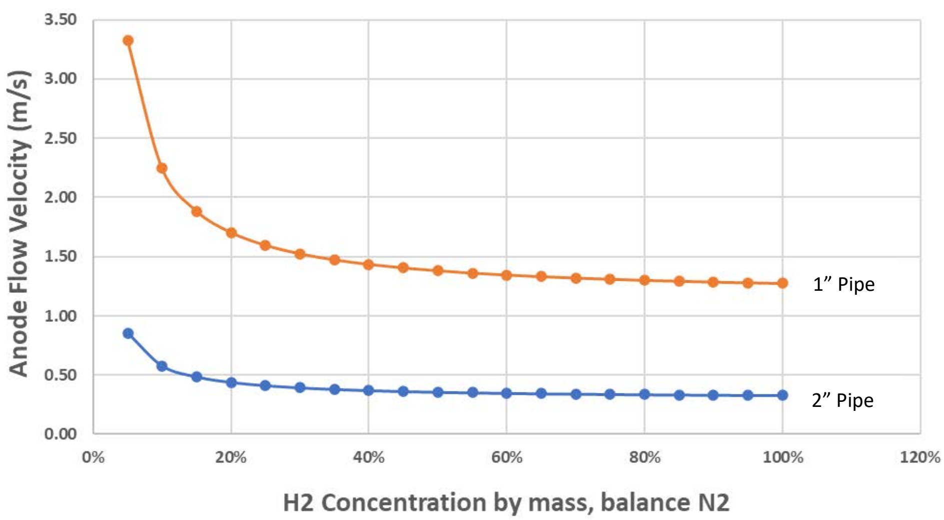


Figure 18. Effect of Hydrogen Concentration on Anode Flow Velocity:
At 500 psig and 80% AES hydrogen recovery.

Source: T2M Global

3D renderings of the near-term and commercial building block designs are shown in **Figure 19** below. The near-term design with 400 cells/stack operating at 300 mA/cm^2 is estimated to produce ~105 kg/day H_2. The commercial design employs 3 times larger area cells, hence 3 times larger production capacity for H_2. This translates to ~315 kg/day H_2 for the commercial building block. T2M has initiated outreach to the current supply chain for the larger capacity hardware components.

Figure 19. AES Building Block → Near-term and Commercial:

Established supply chain for the near-term (100 kg/day) allows rapid deployment.

Source: T2M Global

Long Duration Hydrogen Storage

H_2 energy storage becomes more attractive than battery storage for durations greater than 8 hours. **Figure 20** shows a conceptual design for a complete 100 kW-class AES storage system. 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 energy storage becomes more attractive for longer durations. At MW-scale, the H_2 storage becomes more competitive. As discussed later in the technoeconomic analyses for commercial-scale deployment, AES offers near-term H_2 production cost of $4/kg with a path to <$2/kg identified.

Integrated Storage: The layout shown in **Figure 20** provides a compact footprint, while at the same time enabling easy access for installation and maintenance. The AES module is raised off the ground for enhanced safety and to minimize exposed process pipes and cables. This design allows for easy addition of hydrogen storage behind or to the sides of the module. T2M has connected with another of NETL's contractors, WireTough Cylinders, LLC (WireTough). WireTough is a technology company that is focused on developing and manufacturing pressurized cylinders that combine commercially available components to create breakthrough products that exceed current cycle life, capacity and safety metrics at a competitive price. They provide lightweight steel liners wrapped in proprietary steel wire. These have the potential to provide lower-cost ground storage for hydrogen. WireTough is developing H_2 storage tanks with three different maximum operating pressures (MOP). This provides T2M options to meet site-specific requirements for storage pressure, quantity of stored hydrogen and footprint.

Figure 20. AES Energy Storage - Complete 100 kW Building Block:

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

Source: T2M Global

Pipeline Storage - Hawaii: Hawaii Gas currently has 1100 miles of SNG pipelines containing 10% to 15% H_2. This translates to an immediate potential of 500 tons/year H_2 production using AES. Hawaii Gas' path toward decarbonization in the near-term includes increasing the percentage of H_2 in its fuel mix to 20%, with higher H_2 concentrations planned in the future. **Figure 21** below shows the near-term and future potential of H_2 storage capacity in Hawaii Gas' pipeline. In support of Hawaii Gas' plans to increase the H_2 concentration in their pipelines, T2M, working with our expert advisors in SNG/RNG production, successfully analyzed scenarios to increase H_2 concentration to 20%. These scenarios identified low-cost, near-term upgrades and modifications to their SNG, RNG, and H_2 equipment and processes, including by incorporating AES in their production processes. These analyses have resulted in pathways to achieve 20% H_2 in their pipeline and have been well received by Hawaii Gas as a major opportunity for decarbonization while creating economic opportunities.

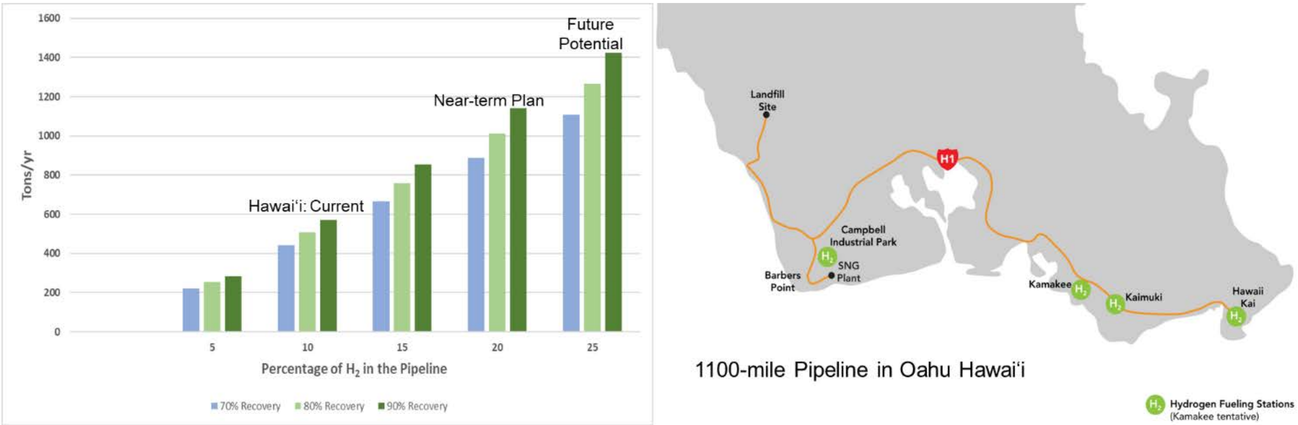


Figure 21. Potential for >1000 ton/year of H_2 → >$10 Million/year Revenue:

Pipeline pressure varies from 500 psi to 300 psi.

Source: T2M Global

Pipeline Storage - US: The potential H_2 production using AES increases dramatically when the US pipeline is used for H_2 storage, **Figure 22**. This provides a highly attractive new pathway for achieving DOE decarbonization goals by adding H_2 to the existing pipeline infrastructure.

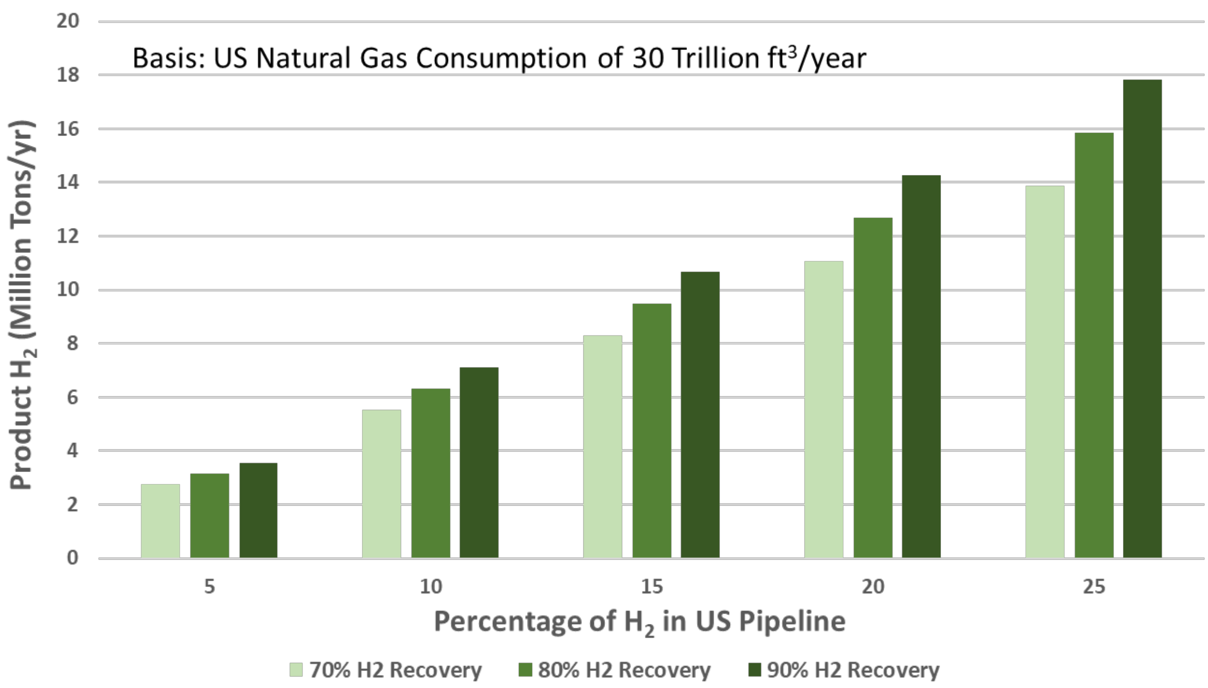


Figure 22. Nationwide Potential for >16 Million Ton/year of H_2:

Huge revenue stream and decarbonization impact.

Source: T2M Global

Technology Gap Assessment

The T2M team developed a technology gap assessment to identify further technology development needed for commercialization by 2030. Gaps include supply chain development for larger capacity cell hardware, designs for reliable operation at higher pressures, thermal management for CapEx reduction.

Strategy for Manufacturing AES in the US

T2M has investigated the initial feasibility of setting up an assembly plant for AES in the US. The team also explored sourcing of supply chain for key components in the U.S.:

- The E-BOP supply chain is well-developed in the US.
- M-BOP supply chain is available: cost-effectiveness needs to be addressed.
- AES cell: Supply is possible. However, the cell size and production capacity need investment to support commercial-scale deployment.
- Multi-purpose vessel fabrication supply chain contacts have been identified.

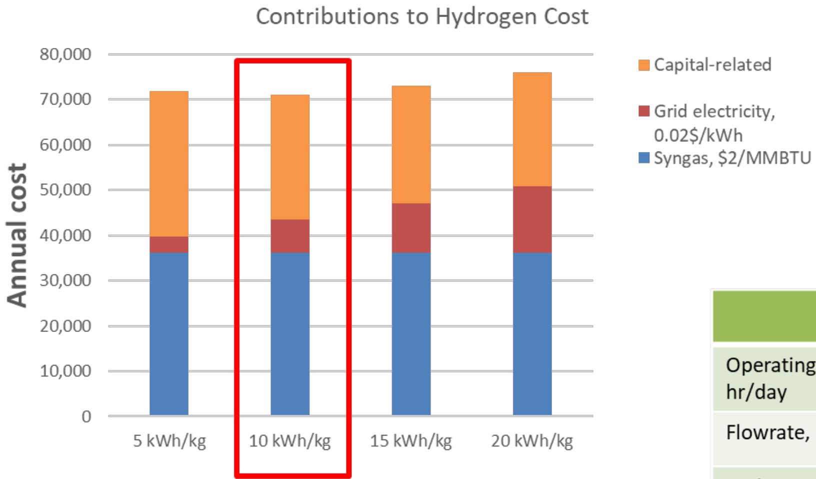
Assembly plant: Locating the AES assembly plant in the US is ideal as the permitting process will be streamlined due to the benign nature of AES stack and system components. Additionally, the well-established US supply chain is synergistic with AES production. This will generate high-paying jobs and benefit disadvantaged communities in the US.

Cost Estimates and Technoeconomic Analysis

Hydrogen energy storage is very promising for long duration applications (>8 hours - where batteries become too expensive to deploy). The cost of H_2 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 the US often leads to curtailments, leading to very low or even negative pricing in some areas in the US. 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/MBTU. 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 23** shows various contributors to AES H_2 production costs and capital costs for different scenarios.



Assumptions:
AES capacity = 100 kg/day
Syngas = $2/MBTU
Grid electricity = 2c/kWh

	5	10	15	20
Operating hr/day	5	10	15	20
Flowrate, kg/hr	20	10	6.7	5
Hydrogen $/kg	2.01	1.99	2.06	2.15

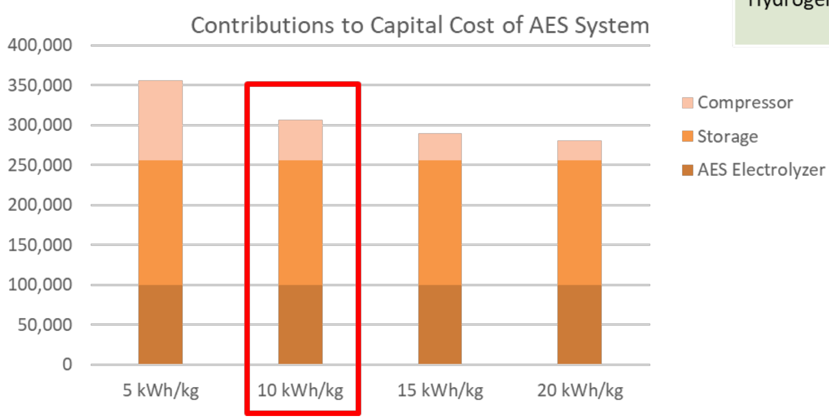


Figure 23. Parametric Analysis - Strategy to Reduce H_2 Production Cost:

Identified pathway to H_2 cost of < $2/kg.

Source: T2M Global

Similar analyses were also performed for varying AES capital costs: $500/kW, $1000/kW, and $1500/kW. The $1500/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[3]. The following is a summary of observations for the value proposition offered by AES-H_2 for LDES applications identified in the TEA:

- The H_2 production cost at $1000/kW of AES capital cost, renewable electricity input cost of 5 cents per kWh, and syngas cost of $2/MBTU was estimated to be about $3 per kg H_2 - significantly better than the target of the project, less than $4/kg.

[3] Sunita Satyapal, Director, Hydrogen and Fuel Cell Technology Office, Overview of DOE Hydrogen Program, Presentation at the Annual Merit Review (AMR), Washington DC, June 2023.

- 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.
- 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, levelized cost of storage (LCOS) of < 10 cents/kWh is projected for the near-term higher capital cost scenario.
- Overall, LCOS of < 5 cents/kWh is achievable with full-scale deployment in LDES markets.
- A DOE-NREL Energy Storage Futures study[4] 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 does not increase with the duration of the storage.

The results of the analyses performed in the TEA show excellent potential of AES as a hydrogen energy storage solution for fossil plants as well as for many other market sectors. Further scaleup and demonstration of cost-effective AES technology is technically and economically feasible and highly warranted for LDES applications.

Conclusions

All goals and objectives for the ultra-low cost H_2 storage system with ultra-high electrical efficiency at competitive costs to make Fossil Power Plants load-following and enhance their value proposition have been successfully accomplished or exceeded. The highly promising results open a new cost-competitive pathway to meet the nation's urgent needs for long-duration storage to retain the value of its excess renewable electricity and decarbonize the fossil industry. Technology scale-up and demonstration steps are highly warranted to advance US zero-carbon goals as highlighted below.

- Verified 1 ton/day recoverable H_2 from Syngas streams available for AES integration at Hawaii Gas.
- Successfully scaled up and validated AES by 100 times, from 0.1 kg/day to 10 kg/day.
- Operated AES stack on simulated syngas streams at <15 kWh/kg H_2.
- Met and exceeded the target of 80% efficiency for energy storage.

[4] Augustine, Chad, and Nate Blair. Energy Storage Futures Study: Storage Technology Modeling Input Data Report. Golden, CO: National Renewable Energy Laboratory. NREL/TP-5700-78694. https//www.nrel.gov.docs/fy21osti/78694.pdf

- Reduced electricity consumption by 80% compared to water electrolyzers.
- Validated AES potential to produce H_2 at less than $4/kg at scale with path to $2/kg identified.
- Reviewed AES integration requirements and benefits for demonstration with Hawaii Gas, target 1 ton/day H_2.
- Successfully analyzed scenarios to increase Hawaii Gas' pipeline H_2 levels to 20%.
- Baseline design for tall stack building block with 100 kg/day, 2.4 MWh/day storage targets has been developed.
- Prototype MW-class module design for Hawaii Gas developed, 1 ton/day H_2 at < 15 MWh/ton.
- Technology Maturation Plan developed for MW-class module.
- Surveyed over a dozen sites as early adopters for deployment.
- Estimates show dilute/waste hydrogen streams have a cumulative potential of over 200,000 GWh/year energy storage for AES to support US decarbonization and grid resiliency goals.
- Utilized guidance from TAC members to identify early adopters for AES-H_2 storage.
- Increased AES technical readiness level (TRL) from 4 to 5.

Recommendations

Future Research and Development Opportunities

The results of AES for fossil plants to store H_2 and provide on-demand power are highly promising. T2M has developed a near-term Technology Maturation Plan to commercialize AES as illustrated in **Figure 24**. The following 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-class AES building block.
- Field demonstration of the 100-kW class building block at Hawaii Gas and/or other high value fossil site.
- Further scaleup to a MW-class prototype: Module designed for manufacturing.
- Behind the Meter demo: Gas Industry and aggregator partnership for monetization.
- Demonstrate cross-cutting application using AES solution for grid support services and upgrading of liquid biofuels to leverage DOE investments, **Figure 25**.
- Engage electric utilities and clean energy stakeholders to develop and demonstrate the value proposition of MW class H_2 energy storage to meet ambitious US carbon reduction goals.

- Deployment plan: Manufacturing development for AES to meet near-term customer needs - supply chain, production lines, assembly plant for early production units.
- Early adopters seeding in niche markets, for example:
    - Fossil plants with waste dilute H_2 streams.
    - Biogas RNG sites: Use of tail gas for H_2 storage.
    - Fuel cell tail gas: At fuel cell power plant sites.
    - LDES for DoD sites having existing biomass gasifiers.
    - Grid Resiliency: Woodyards: gasifier → H_2 storage (MW module).
    - DC Microgrids for data centers.
    - Hybrid energy storage system: EPRI, IOUs.
- Develop and validate Multi-Purpose Energy Station for EV-charging, fuel cell electric vehicle (FCEV) refueling, and grid support.

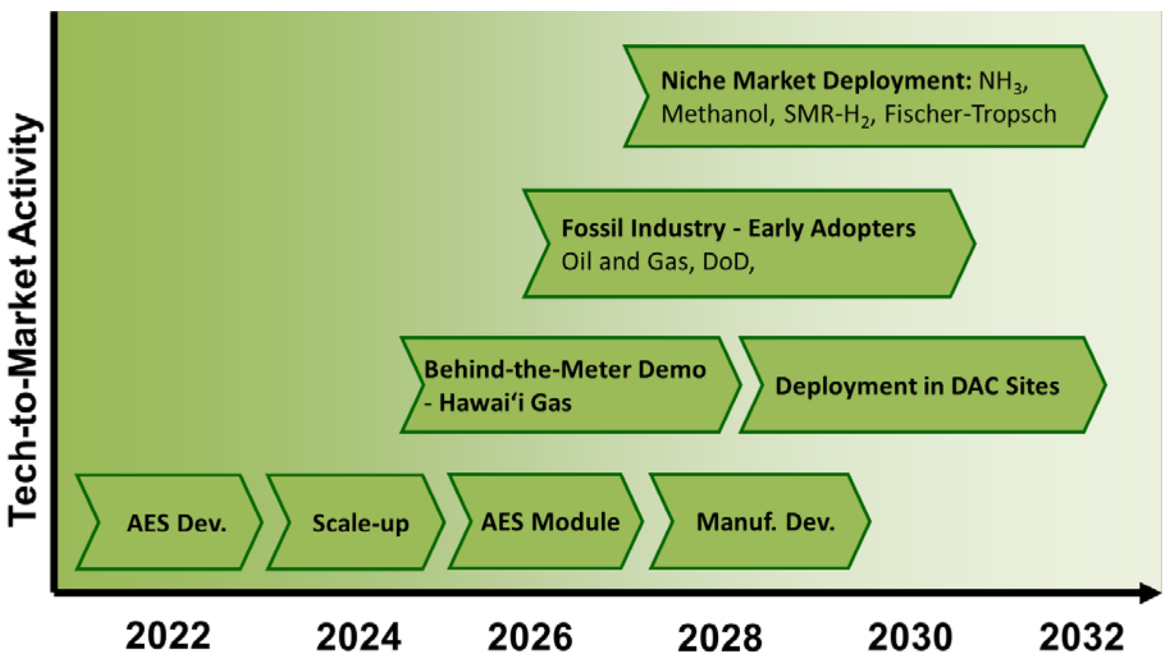


Figure 24. Roadmap for AES Commercialization:

Next steps – technology scale-up, validation, and manufacturing development.

Source: T2M Global

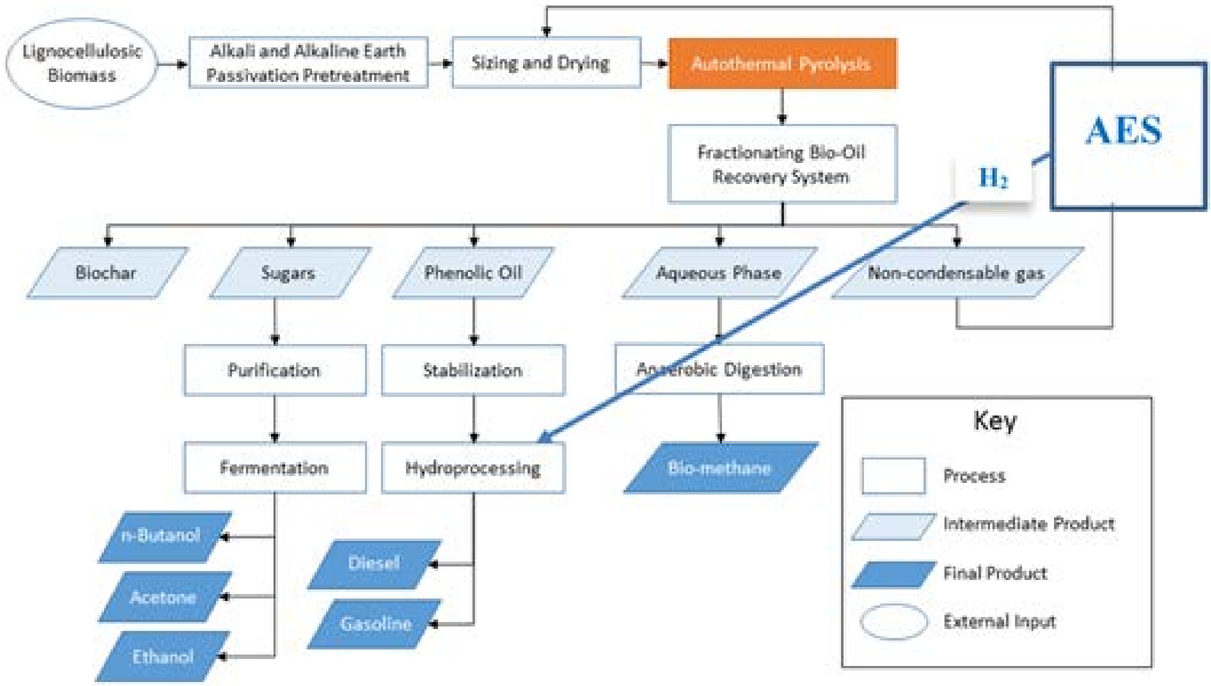


Figure 25. Multipurpose Solution for Cross-cutting Applications:

H_2 energy storage for grid support and upgrading liquid biofuels.

Source: T2M Global

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Appendix A: Acronyms and Other Abbreviations Used in this Report.

AC – Alternating Current

ADG – Anaerobic Digester Gas

AES – Advanced Electrolyzer System

B – Billion

BOP – Balance of Plant

BTU – British Thermal Unit (1 kWh = 3413 BTU)

CapEx – Capital Expenditure

CEO – Chief Executive Officer

CFO – Chief Financial Officer

CH_4 - Methane

cm^2 – Centimeter Squared

CO – Carbon Monoxide

CO_2 – Carbon Dioxide

CO_2e – Carbon Dioxide Equivalent

DAC – Disadvantaged Community

DC – Direct Current

DoD – Department of Defense

DOE – Department of Energy

E-BOP – Electrical Balance of Plant

EPRI – Electric Power Research Institute

EV – Electric Vehicle

FCEV – Fuel Cell Electric Vehicle

FT – Fischer-Tropsch

GHG – Greenhouse Gasses

H_2 – Hydrogen

H_2O – Water

IOU – Investor-Owned Utility

kg – Kilogram

kWh / MWh / GWh – Kilowatt Hour / Megawatt Hour / Gigawatt Hour

LCOE – Levelized Cost of Energy

LCOS - Levelized Cost of Storage

LDES – Long Duration Energy Storage

mA – Milli-ampere

M-BOP – Mechanical Balance of Plant

MM – Million

N_2 – Nitrogen

NETL – National Energy Technology Laboratory

NH_3 – Ammonia

O_2 – Oxygen

OpEx – Operating Expenses

PLC – Programmable Logic Controller

PSA – Pressure Swing Absorber

psi – Pounds per Square Inch

psig – Pounds per Square Inch Gauge

R&D – Research and Development

RNG – Renewable Natural Gas

SMR – Steam Methane Reforming

SNG – Synthetic Natural Gas

Syngas – Synthesis Gas

T2M – T2M Global, LLC

TAC – Technical Advisory Committee

TEA – Technoeconomic Analysis

TRL – Technology Readiness Level

UPS – Uninterruptable Power Supply

VRE – Variable Renewable Energy

W / kW / MW – Watt / Kilowatt / Megawatt (1 MW = 1000 kW / 1 kW = 1000 W)