Key Performance Indicators (KPIs) and Technoeconomic Analysis (TEA) of a Novel Polymer Electrolyzer Using Seawater Feedstock

Cooperative Research and Development Final Report

CRADA Number: CRD-22-23259

NREL Technical Contact: Alex Badgett

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Contract No. DE-AC36-08GO28308

Technical Report
NREL/TP-6A20-87737
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National Renewable Energy Laboratory
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Report Date: October 2, 2023

In accordance with requirements set forth in the terms of the CRADA agreement, this document is the CRADA final report, including a list of subject inventions, to be forwarded to the DOE Office of Scientific and Technical Information as part of the commitment to the public to demonstrate results of federally funded research.

Parties to the Agreement: Evolve Hydrogen, Inc.

CRADA Number: CRD-22-23259

CRADA Title: Key Performance Indicators (KPIs) and Technoeconomic Analysis (TEA) of a Novel Polymer Electrolyzer Using Seawater Feedstock

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Sponsoring DOE Program Office(s):

Office of Energy Efficiency and Renewable Energy (EERE), Hydrogen and Fuel Cell Technologies Office (HFCT)

Joint Work Statement Funding Table showing DOE commitment:

Estimated Costs	NREL Shared Resources a/k/a Government In-Kind
Year 1	$50,000.00
TOTALS	$50,000.00

Executive Summary of CRADA Work:

The goal of this project is to perform supporting modeling and analysis of Evolve Hydrogen's novel polymer electrolyzer utilizing seawater and other common water feedstocks for KPIs and to perform technoeconomic analysis.

CRADA benefit to DOE, Participant, and US Taxpayer: Uses the laboratory's core competencies.

Summary of Research Results:

Purpose:

Evolve Hydrogen Inc., ("EHI") has developed a novel polymer electrolyzer which has been analyzed at three New York State universities. The reactive materials of EHI's polymer electrolyzer are being analyzed by two international universities. The polymer nature of the reactive materials allows for electrolysis of any water feedstock while maintaining competitive efficiencies and durability.

This collaboration will determine (1) Key Performance Indicators (KPIs) of the latest EHI's prototype in various water feedstock, specifically seawater (simulated), (2) a Technoeconomic Analysis (TEA) of the electrolyzer based on the KPIs identified and agreed upon by the Parties, and (3) a sensitivity analysis to guide KPI advances, reducing the cost of EHI's novel polymer electrolyzer.

TASK DESCRIPTIONS:

Task 1: *The Participant will deliver design details for the electrolyzer prototype to the Contractor. The Participant will provide background on the functioning of the electrolyzer prototype to the Contractor.*

Task 1 Results:

EHI delivered design prototypes for the Evolve™ 37-Cell to NREL, and testing results for the Evolve™ 7-Cell electrolyzer under various feedstock and power scenarios, which was used for the subsequent analysis and calculation. NREL analyzed the system cost, electrolyzer capital cost, efficiency, and balance of plant (BOP) for the prototype in Task 1.

System Cost:

(1) Electrolyzer capital cost - $/kW

Stack material cost for a single unit of 37-cell electrolyzer is calculated as below in Table 1:

Key Components	Material type	Volume (mm3)1	Material usage (kg)2	Material cost ($/kg)3	Material Cost ($)
Lid	Polypropylene (PP)	314000	0.28888	$1.29	$0.37
Oxygen Trap	PP	343000	0.31556	$1.29	$0.41
Anode Spike	Polyphenylene Sulfide (PPS)	136017	0.18362	$178.37	$32.75
Collector Tubes	PPS	535404	0.72279	$178.37	$128.93
Cathode Matrix	PPS	179856	0.24281	$178.37	$43.31
Redox Chamber	PP	450000	0.41400	$1.29	$0.53
Base Station	PP	464000	0.42688	$1.29	$0.55
Total					$206.84

Based on the Pro Forma Consolidated Statement of licensing Evolve™ 37-Cell technology, which accounted for material, production, and wage costs and average pricing for utilities and lease in Nassau, and Suffolk County, New York, U.S., the additional cost for production facilities, human resources, and injection molding for one electrolyzer unit is ($3,440,294-$963,094)/21,000 = 117.96 $/unit.

Therefore, a single Evolve unit costs around ($206.84+$117.96)=$324.8, due to data gap for the 7-cell unit, $324.8 is used as proxy for the 7-cell unit for the subsequent analysis. The capacity (kW) for a 7-cell model is estimated to be 13.64kW, based on 3 kg H2 / day production capacity and the electrolyzer efficiency of 109.1kWh/kg when using simulated seawater as feedstock. Thus, the average electrolyzer capital cost is $324.8/13.64kW =$23.81/kW.

(2) Balance of plant (BOP) that includes upstream and downstream of the electrolyzer:

From the H2A model for current distributed PEM electrolysis, a system with 3 kg H_2 / day production[4], capacity and the electrolyzer efficiency of 109.1kWh/kg has a BOP cost of $183.91/kW. We assume the BOP cost is $183.91/kW for preliminary analysis.

[1] Parts' volumes are estimated based on the SolidWorks file provided by EHI.
[2] Material usage in kg is estimated by using the density of PPS (1.35 g/cm^3) and PP (0.92 g/cm^3).
[3] Material cost for PP: Statista. "Global Average Price of Polypropylene Forecast from 2018 to 2023." Statista, https://www.statista.com/statistics/1171084/price-polypropylene-forecast-globally/#:~:text=In%202021%2C%20the%20global%20average,1%2C208%20U.S.%20dollars%20per%20ton
Material cost for PPS is based on the pricing sheet shared by EHI
[4] This daily production capability is projected for the C-37 unit.

Task 2: *The Contractor will identify input parameters (KPIs) and key assumptions for economic models (e.g., hydrogen analysis ("H2A")), and provide to the Participant. The Participant will determine the KPIs of the electrolyzer in various water feedstocks and provide them to the Contractor. Based on the KPIs and the key inputs provided by the Participant, the Contractor will perform TEA analysis on the electrolyzer.*

Task 2 Results:

Based on the results from Task 1, NREL identified key performance indicators (KPI) for the techno-economic analysis (TEA) in H2A-Lite. EHI provided testing results for such KPIs under various water feedstocks, and TEA results are shown below:

Scenario Design:

1. Electrolyzer cost and efficiency cases provided by EHI:

Table 2: Electrolyzer cost and efficiency cases

#	Scenario	Voltage (V)	Electrolyzer capital cost ($/kW)	Balance of plant capital cost ($/kW)	H2 Production Efficiency kg/kWh x105	Electrolyzer efficiency (kWh/kg H2)	Balance of plant efficiency (kWh/kg H2)
(1)	Simulated Tap water[5]	48	23.81	183.91	82.4	1213.6	1213.6
(2-1)	Simulated Seawater[6]	5	23.81	183.91	916.8	109.1	109.1
(2-2)	Simulated Seawater[7]	48	23.81	183.91	468.4	213.5	213.5
(3)	Target Efficiency case	N/A	23.81	183.91	N/A	48	48

[5] "Gilman Executive Summary Report", March 7, 2022, Simulated tap water testing results for 48V
[6] "Gilman Executive Summary Report", March 7, 2022, Simulated seawater testing results for 5V
[7] "Gilman Executive Summary Report", March 7, 2022, Simulated seawater testing results for 48V

Cases (1), (2-1), and (3) are used for subsequent analysis for Task 2.

2. Hydrogen Production Credit (PTC):

Section 45V from the Inflation Reduction Act of 2022 defines production credit for clean hydrogen[8]. Qualified hydrogen credits are determined by the lifecycle greenhouse gas emission rate and prevailing wage and apprenticeship requirements. The base hydrogen credit is $0.6/kg, if the greenhouse gas emissions rate is less than 0.45 kilograms of CO_2e per kilogram of hydrogen, the top rate is five times the amount of the base credit, which tops out at $3.0/kg of qualified clean hydrogen produced. Hydrogen PTC applies to hydrogen produced after December 31, 2022, for 10 years.

We usually discounted the credit value because we factor in additional costs such as the emission rate verification, legal, due diligence as well as tax equity financing. However, the rollout of the IRA made claiming incentive credits easier. We will use the full amount of $3.0/kg as clean hydrogen PTC proxy or subsequent analysis. We assume no hydrogen PTC when sourcing electricity from direct grid-tied generation and wholesale power market, as the carbon emissions of such electricity are difficult to measure and verify; and we use top hydrogen PTC of $3.0/kg when sourcing electricity from wind power purchase agreement (PPA) and offshore wind coupling.

[8] Bloomberg Tax, "Sec. 45V. Credit For Production Of Clean Hydrogen", https://irc.bloombergtax.com/public/uscode/doc/irc/section_45v

3. Electricity supply and system deployment scenarios:

Table 3 Electricity Supply Scenario Summary

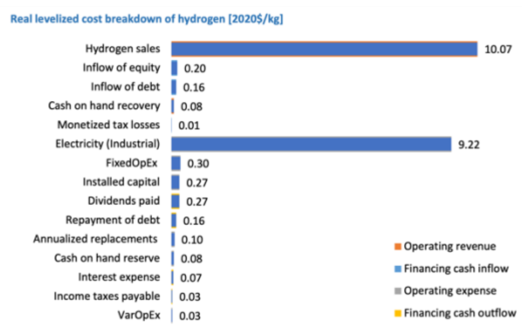
Electricity supply configuration	Definition and notes	Electricity Cost & capacity factor	Hydrogen PTC	Sources
(1) Direct grid-tied	Electrolyzer is directly tied to the grid and pays retail industrial electricity rates. Represents conventional electrolyzer operation	84.5 $/MWh, 97%	N/A	EIA, Electric Power Monthly, "Average Price of Electricity to Ultimate Customers"9
(2) Generic wind power purchase agreement	Electrolyzer is assumed to enter into a power purchase agreement (PPA) with a wind generator. Can leverage market data on wind PPAs to estimate a likely cost of electricity and operating capacity factor.	35-310 $/MWh depending on the PPA contracted amount (MW) and the projects, 39% (see Appendix)	$3/kg	BloombergNEF provides such historic PPA costs for onshore wind10, we used all available data for the northeast region (see Appendix, Figure x)
(3) Wholesale power market	Electrolyzer operating in a wholesale power market with an hourly variable pricing scheme. The system will cycle frequently on and off, likely impacting the electrolyzer lifetime.	Depending on the capacity factor of the electrolyzer, the rolling average of hourly electricity price ranges between 13 to 38 $/MWh, 0-100% (see Appendix)	N/A	NREL Cambium dataset provides such hourly electricity production rate11 (see Appendix, Figure x)
(4) Offshore wind coupled	Electrolyzer located offshore directly connected to offshore wind. Electricity costs and capacity factor from offshore wind modeling at NREL. System will cycle frequently on and off, likely impacting electrolyzer lifetime. System likely to require additional balance of plant equipment.	$0.075/kWh, 45%	$3/kg	NREL Annual technology baseline dataset12 for offshore wind technical potential cost

[9] EIA, Average Price of Electricity to Ultimate Customers, https://www.eia.gov/electricity/monthly/epm_table_grapher.php?t=epmt_5_03, accessed May 2023.
[10] Bloomberg NEF. 2020. "2020 U.S. Renewable PPA Price Data."
[11] Cambium, https://www.nrel.gov/analysis/cambium.html
[12] NREL Annual Technology Baseline, https://atb.nrel.gov/electricity/2022/offshore_wind

Discussion and results summary:

1. The electricity cost is the main driver of the hydrogen levelized cost generated by EHI's electrolyzer:

1) Higher efficiency electrolysis system lowers the amount of electricity needed. Figures 1 and 2 below demonstrate the cost of hydrogen when sourcing electricity from the grid. The lower efficiency scenario of 109 kWh/kg doubles the cost compared to the target case of 48 kWh/kg.



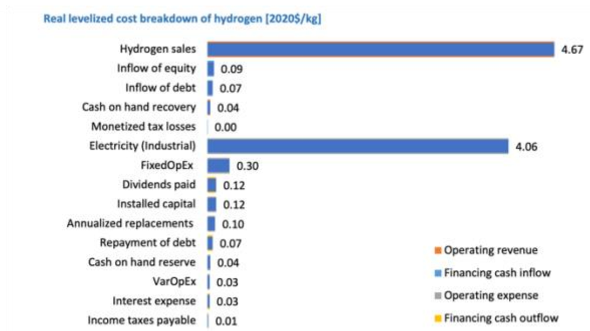


Figure 1: Cost Breakdown for Case 2-1 (109kWh/kg). Figure 2: Cost Breakdown For Target Efficiency (48kWh/kg)

2) Electricity supply cases:

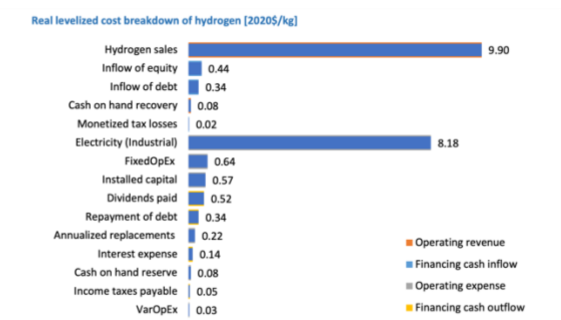
If the electrolyzer can be operated flexibly as a demand response system, it can assess electricity from wind power purchase agreements or the wholesale power market as a real-time pricing program. Electrolyzer operators can have the system on standby or shutdown mode when the electricity cost is high or when cost-effective wind-generated electricity is not available. Direct grid-tied electricity may provide higher capacity factor, but the emission impact is relatively difficult to quantify. The wholesale power market also provides attractive and low-cost electricity, although we did not include the additional markups from the utility that provides the service besides a basic 7% adder. Frequent ramping up and down of the system might have a significant impact on electrolyzer lifetime, for this analysis, we will not quantify such impacts. The table below shows the hydrogen levelized cost (HLC) for each supply scenarios.

Table 4 Hydrogen Levelized Cost Summary Table

Electricity supply configuration	Supply Cases	Overall Efficiency (kWh/kg)	Electrolyzer lifetime impacts (qualitative)	H2A Calculated HLC w.o IRA ($/kg)	HLC w. Hydrogen Tax Credit ($/kg)
(1) Direct-grid tied	(1) Tapwater	1213.6	Minimal	108.7	n/a
	(2-1) Seawater	109.1		10.1	
	(3) Target	48		4.7	
(2) Generic wind power purchase agreement	(1) Tapwater	1213.6	Moderate	120	115.9
	(2-1) Seawater	109.1		11.7	7.7
	(3) Target	48		5.7	1.7
(3) Wholesale power market	(1) Tapwater	1213.6	Significant	47.4 @ 65% CF	n/a
	(2-1) Seawater	109.1		5.1 @ 81% CF	
	(3) Target	48		2.5 @ 87% CF	
(4) Offshore wind coupled	(1) Tapwater	1213.6	Significant	101	96.9
	(2-1) Seawater	109.1		9.9	5.8
	(3) Target	48		4.9	0.8

2. Hydrogen credits provided monetized benefits to the system

Fully hydrogen tax credits only apply to low greenhouse emission (less than 0.45 kilograms of CO2e per kg of H_2) hydrogen that meet prevailing wage labor requirements. Figure 3 and 4 below demonstrates without and with hydrogen tax credit from the IRA, the $3/kg financial incentives result in $4/kg monetized tax losses.



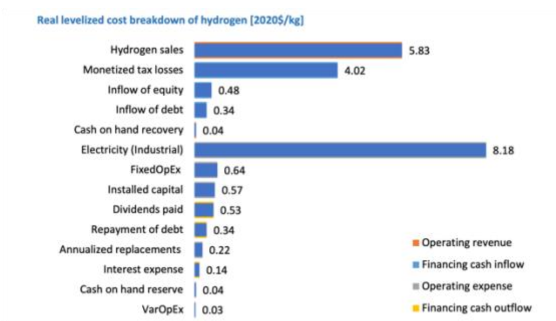


Figure 3: Cost Breakdown for case 2-1 without IRA credit. Figure 4 Cost Breakdown for case 2-1 with IRA credit

Task 3: *The Contractor will perform sensitivity analysis on KPIs, the Participant is expected to review the inputs and key results with the Contractor*.

Task 3 Results:

For Task 3, NREL documented the key performance indicators (KPI) and sensitivity analysis around EHI's electrolyzer system, NREL also identified data and testing gap for the next phase of the analysis.

Major KPI for Electrolysis System:

1. Efficiency Improvement:

Efficiency play a critical role in hydrogen cost-effectiveness and the viability of the electrolysis system. The current testing data shows varying hydrogen production efficiencies at different voltage levels. For instance, seawater demonstrated the highest efficiency at 5 volts and 1.3 amps, achieving 916.8 kg/kWh x 10^{-5}, which corresponds to 35% of the theoretical maximum. To meet the target efficiency of 0.02 kg/kWh, the system needs to achieve an additional 50% improvement from the highest recorded efficiency.

2. Advancing Polymer Electrolytical Properties:

The EHI team is actively researching nickel-embedded polymers to enhance the performance of the electrolysis system. These advancements in polymer electrolytical properties may promote improvement in system efficiency. By leveraging innovative materials, the goal is to boost the overall efficiency of the electrolysis process, thereby reducing operational costs and increasing hydrogen production rates.

3. Comparative Scenarios:

For Task 2, we have evaluated simulated scenarios with different electrolyzer voltages, electrolyzer capital costs, and Balance of Plant (BOP) capital costs as well as different supply scenario. Each scenario represents unique system configurations and associated efficiency. For example, simulated seawater electrolysis at 5 volts achieved an impressive efficiency of 916.8 kg/kWh, while seawater electrolysis at 48 volts reached 468.4 kg/kWh. Understanding these scenarios and their related costs is crucial in guiding future design and engineering decisions.

4. Role of Balance of Plant (BOP):

The Balance of Plant (BOP) encompasses all supporting components and systems needed to ensure the electrolysis process runs efficiently and reliably. The EHI system encompasses a unique hydride system, which is not studied extensively yet. These components include dryer, compressors, chiller, storage tank, controls, and other safety measures. The BOP capital cost is a key consideration in the overall cost structure of the electrolysis system.

5. Addressing Data Gaps:

Efficiency testing and characterization are vital aspects that require further investigation through future testing. Identifying data gaps and conducting comprehensive testing will provide valuable insights into system performance, helping engineers and researchers optimize the electrolysis process for improved efficiency and durability.

6. Benchmarking:

EHI has an innovative seawater electrolysis system, developing a comprehensive benchmarking database is beneficial for assessing electrolysis system performance. By collecting and analyzing efficiency testing and characterization data, this benchmarking initiative will enable us to compare and evaluate different electrolysis setups. It will serve as a valuable resource for identifying best practices, understanding trends, and setting realistic efficiency improvement targets.

By prioritizing efficiency improvements and exploring innovative materials, the electrolysis system can make substantial progress in hydrogen production. Evaluating different scenarios and understanding the role of the BOP will enable cost-effective and reliable integration of the electrolysis system in various applications. Addressing data gaps and creating a benchmarking database will further refine the electrolysis process and advance commercialization.

Task 4: *The Participant and Contractor will co-draft the CRADA Final Report and submit in accordance with the terms of this Agreement.*

Task 4 Results:

This report serves to meet the requirement for the CRADA Final Report with preparation and submission in accordance with the agreement's Article X.

Additional Tasks- Other work at the direction of the Participant, consistent with the scope and subject to the availability of funding.

<u>Subject Inventions Listing</u>: None

<u>ROI #</u>: None