H2NEW
Hydrogen from Next-generation Electrolyzers of Water
U.S. DEPARTMENT OF ENERGY

H2NEW: Hydrogen (H2) from Next-generation Electrolyzers of Water LTE Task 3c: System and Techno-economic Analysis

Bryan Pivovar, NREL; Mark Ruth, NREL; Rajesh Ahluwalia, ANL

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Project ID # P196D

Task Team Members

Mark Ruth (NREL):
Subtask lead

Alex Badgett (NREL):
Technoeconomic and manufacturing analysis

Rachel Rubin (NREL):
PyFast tool development

Amogh Thatte (NREL):
Manufacturing analysis

Joe Brauch (NREL):
Manufacturing analysis

Rajesh Ahluwalia (ANL):
Performance modeling lead

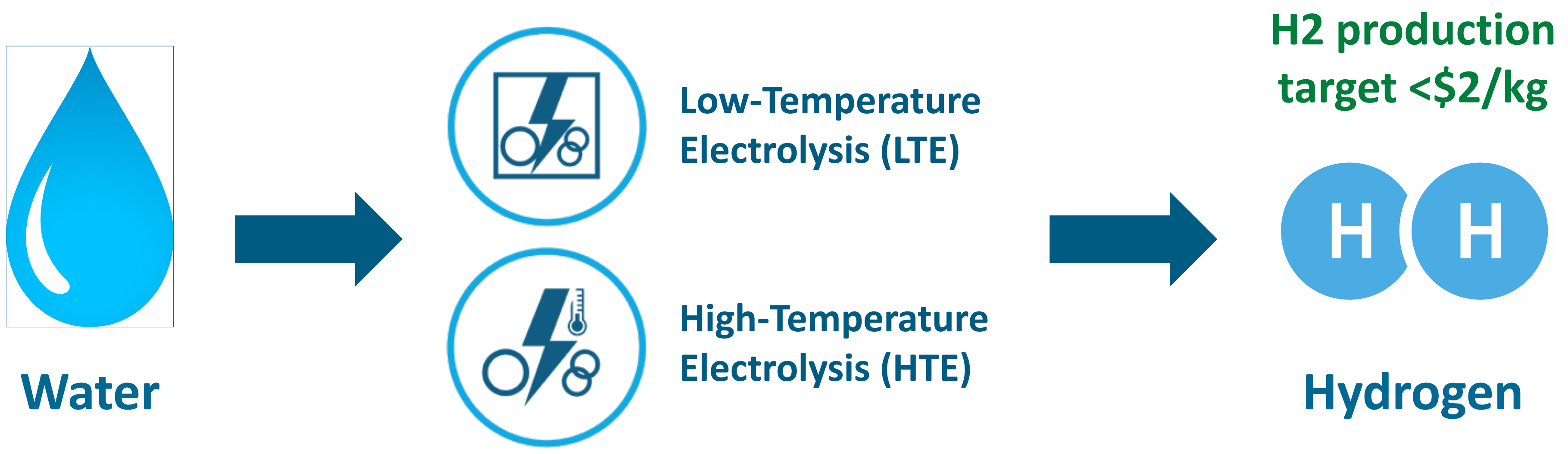
Xiaohua Wang (ANL):
Performance and durability model development

Andrew Star (ANL):
System analysis

Dionissios Papadias (ANL):
Life cycle analysis

Project Goals

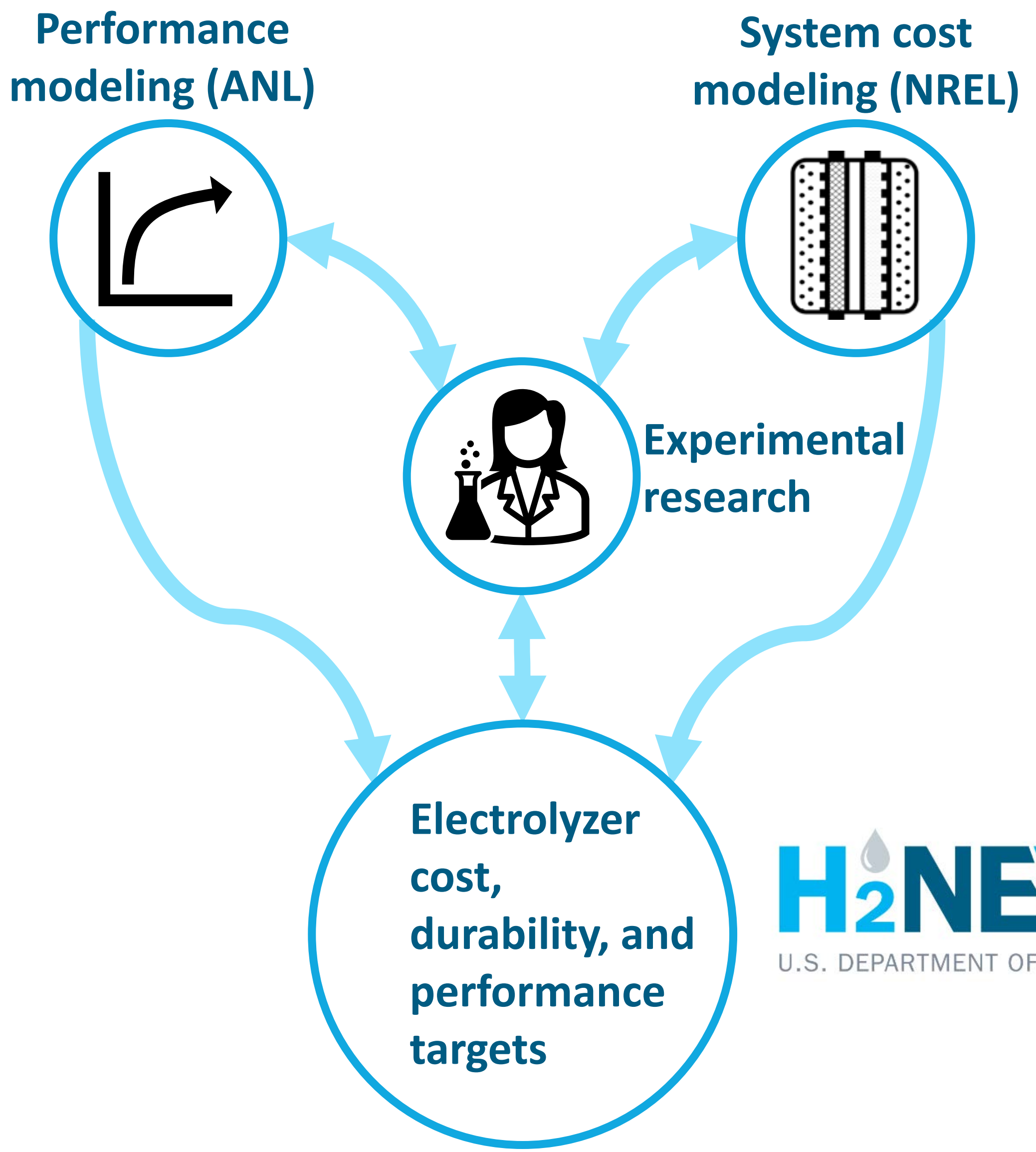
Goal: H2NEW will address components, materials integration, and manufacturing R&D to enable manufacturable electrolyzers that meet required cost, durability, and performance targets, simultaneously, in order to enable $2/kg hydrogen.



H2NEW has a clear target of establishing and utilizing experimental, analytical, and modeling tools needed to provide the scientific understanding of electrolysis cell performance, cost, and durability tradeoffs of electrolysis systems under predicted future operating modes

Task Overview

- This task leverages expertise in system cost and performance modeling from NREL and ANL to benchmark H2NEW cost, durability, and performance targets
- Experimental and analysis capabilities form a crucial feedback loop for validating progress towards H2NEW targets



Overview

Timeline and Budget

- Project start date: 10/1/2021
- FY21 DOE funding (if applicable): $400K - $275K NREL and $125K ANL
- FY22 planned DOE funding: $400K - $275K NREL and $125K ANL
- FY23 planned DOE funding: $400K - $275K NREL and $125K ANL

Barriers

- $2/kg green hydrogen production
- Developing affordable, reliable, and efficient electrolyzers

Partners

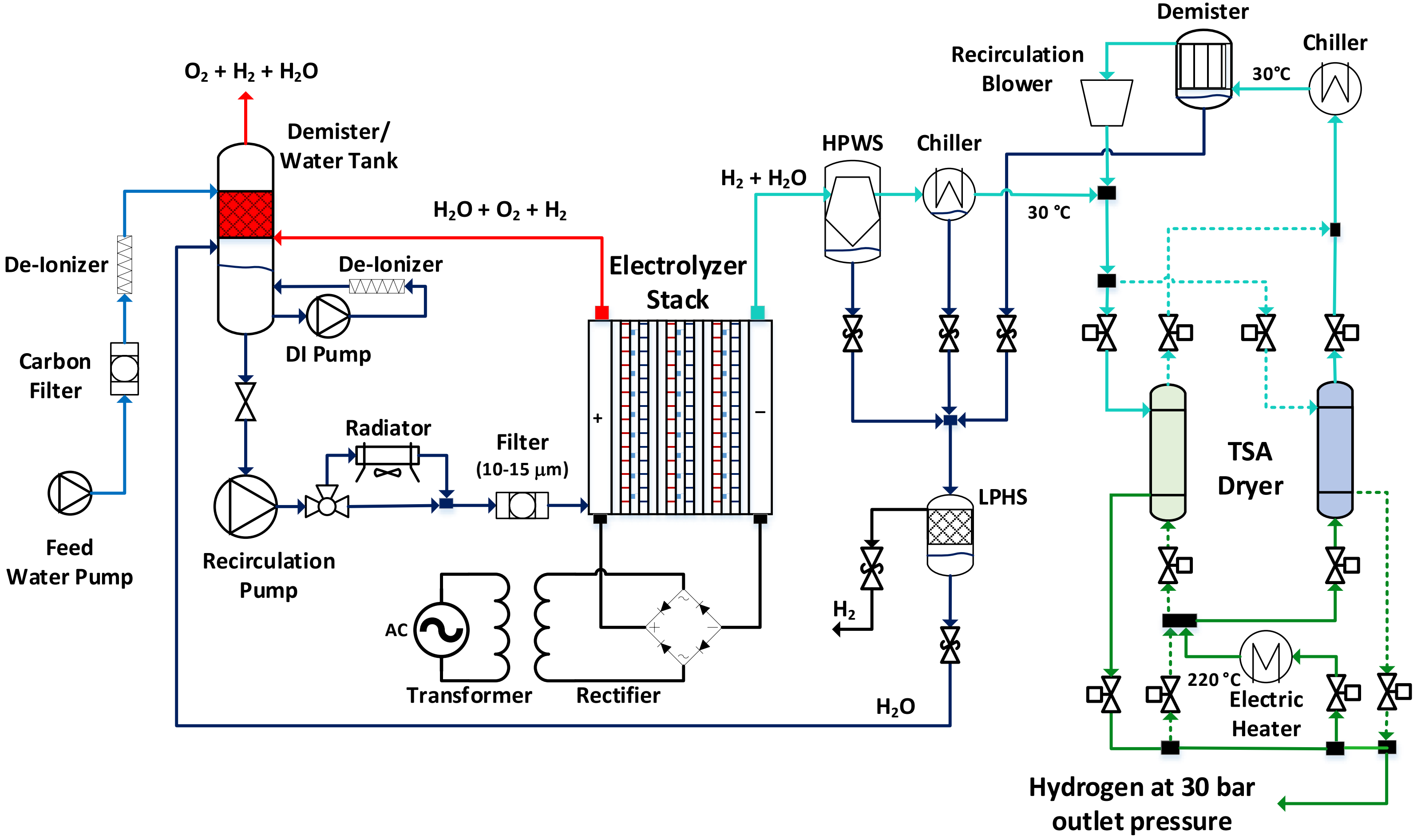
- Project lead: Bryan Pivovar (NREL)
- Task Leads: Rajesh Ahluwalia (ANL) and Mark Ruth (NREL)

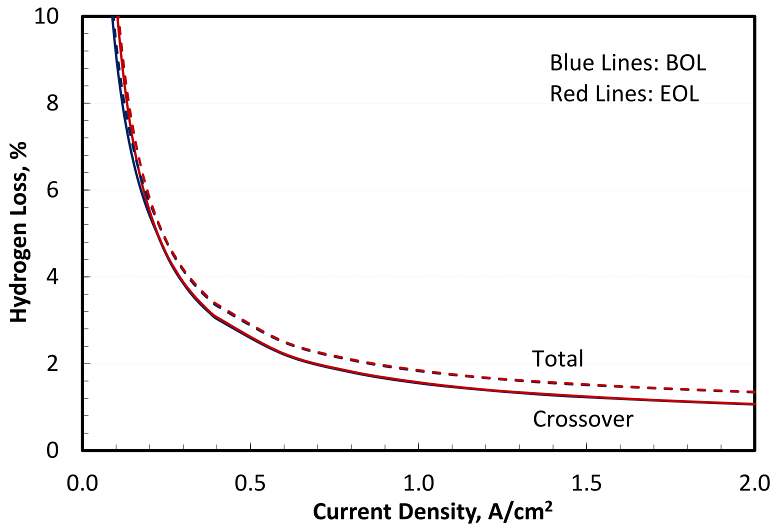
Relevance

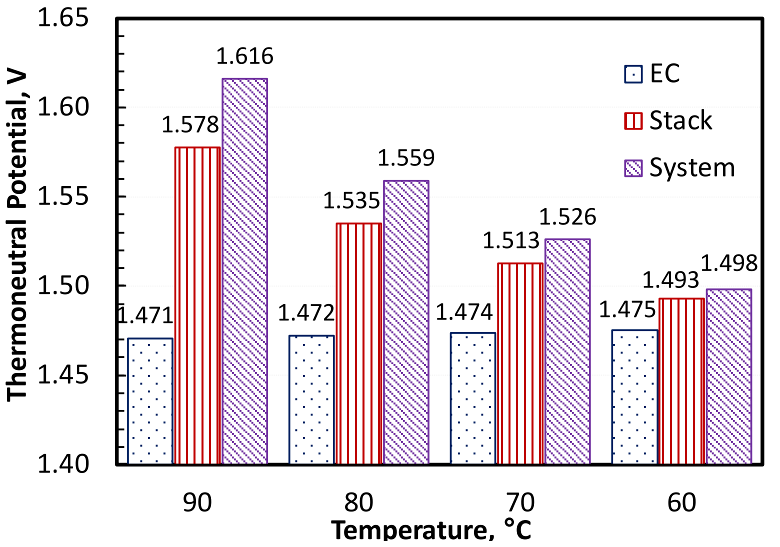
- Enabling the H2NEW project to develop appropriate LTE stack cost, performance, and durability targets by
  - Linking R&D measurements and objectives to performance and economic impacts
  - Providing operating conditions and cycles for consideration and testing
  - Highlighting operating requirements and manufacturability
- Evaluating cost, performance, and durability tradeoffs to determine optimum LTE deployment to achieve $2/kg and $1/kg production cost in renewable energy integration scenarios
- Involves optimization across multiple capabilities
  - System performance and durability assessment
  - Bottom-up manufacturing cost assessment
  - Systems analysis including interactions with the electricity grid and direct connection to renewable energy generation

Approach: Developing a Reference PEM Electrolysis System by Building upon ANL-Developed Design

- GCTool model for accurate representation of the system layout, BOP components and flows
- Model based losses for H_2 losses because of H_2/O_2 crossover, H_2 purge (LPHS), and O_2 removal (DeO_2)
- Parasitic loads: rectifier/transformer, chiller, TSA dryer (regeneration and blower)



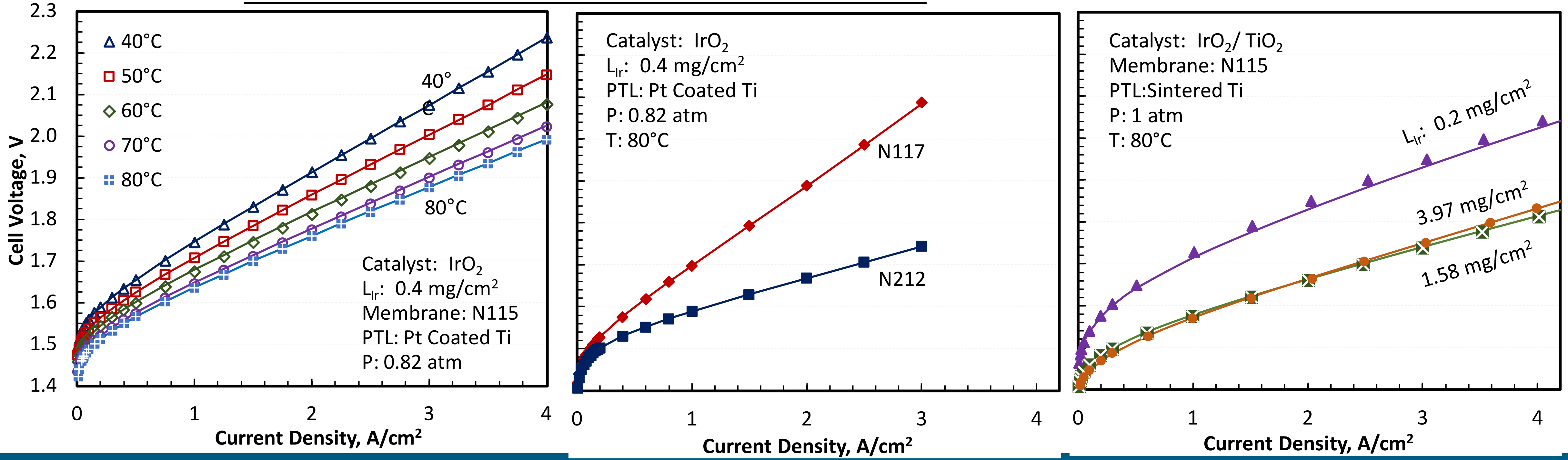




Approach: Validate System Performance and Durability Models against H2NEW Data

Data Source	OER Catalyst	L_{Ir} mg/cm^2	PTL	Membrane	T °C	b mV	i_0 μA/cm^2
NREL	IrO_2	0.4	Pt Coated Ti	N115	40	21.0	0.020
					50		0.035
					60		0.047
					70		0.071
					80		0.043
NREL	IrO_2	0.4	Pt Coated Ti	N117	80	24.5	0.231
				N212		24.9	0.360
JECS 2018	IrO_2/TiO_2	0.2	Sintered Ti	N212	80	28.1	0.277
		1.58				18.9	0.032
		3.97				18.0	0.034

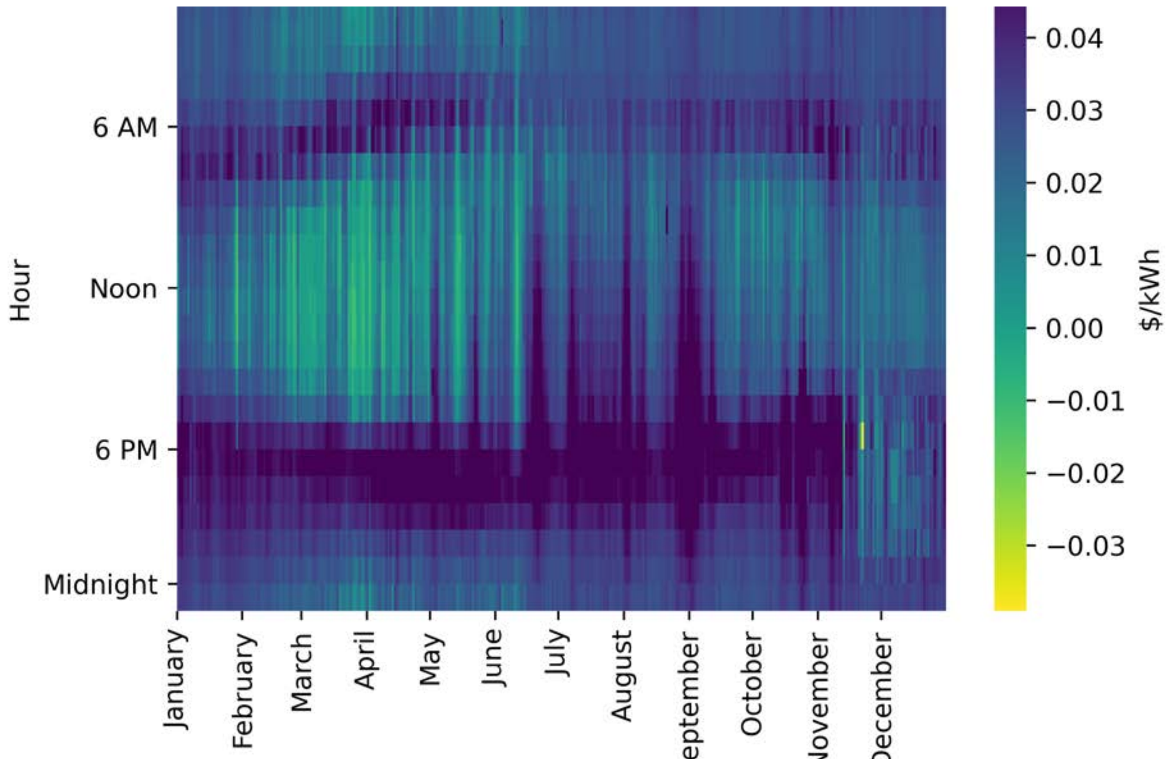
- L_{Ir}: Iridium loading in anode catalyst, mg/cm^2
- b : Tafel slope parameter, mV/dec
- i_0: Exchange current density, μA/cm^2



Approach: Optimal Operations Strategy for a Variety of Electricity Sources and Prices

- Electricity prices are going down and becoming more volatile as wind and photovoltaic (PV) solar generation increases.
- Intermittent operation at wholesale LMPs provides opportunities to decrease cost
- Task involves identifying operating strategy necessary to achieve low prices and potential impacts on durability

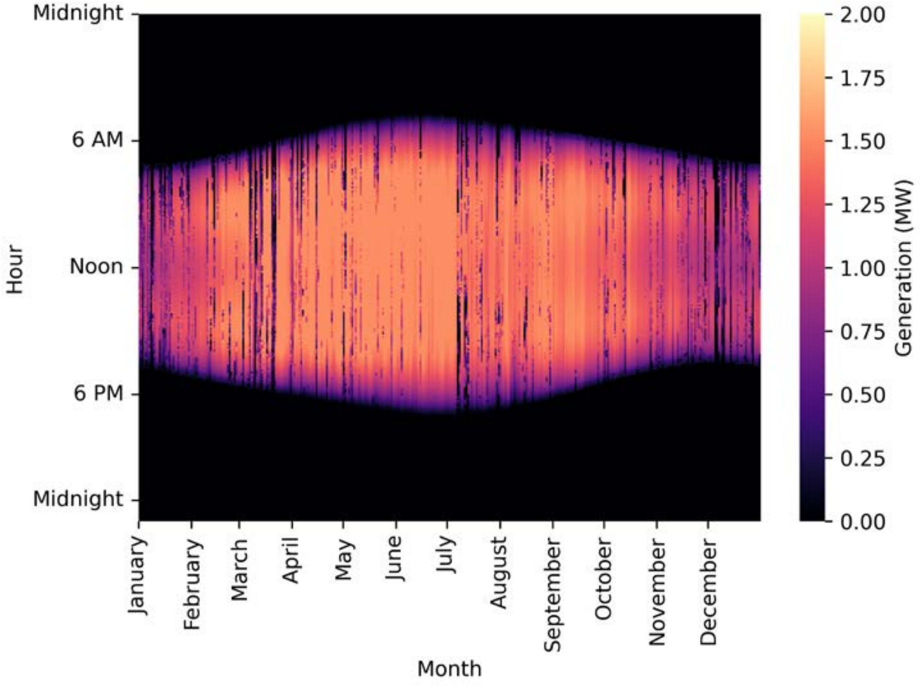
Locational Marginal Electricity Prices (LMPs) for California ISO Palo Verde Node in 2017



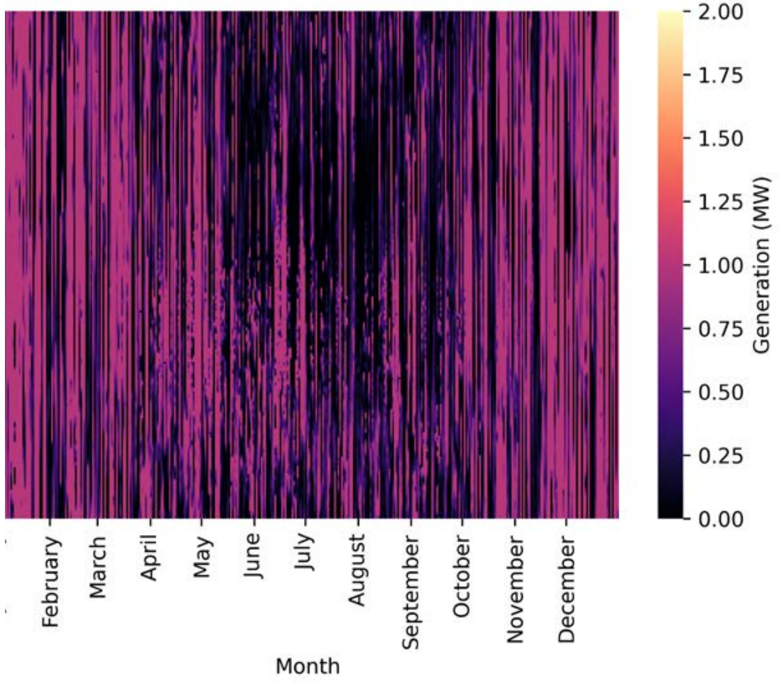
Approach: Optimal Operations Strategy for a Variety of Electricity Sources and Prices

- Task also involves analyzing LTE electrolyzers directly connected to wind and photovoltaic solar electricity generation
- NREL PySAM modeling platform is used to simulate outputs from PV/wind at any location or capacity
- Battery energy storage can also be added to the electrolyzer-renewable system

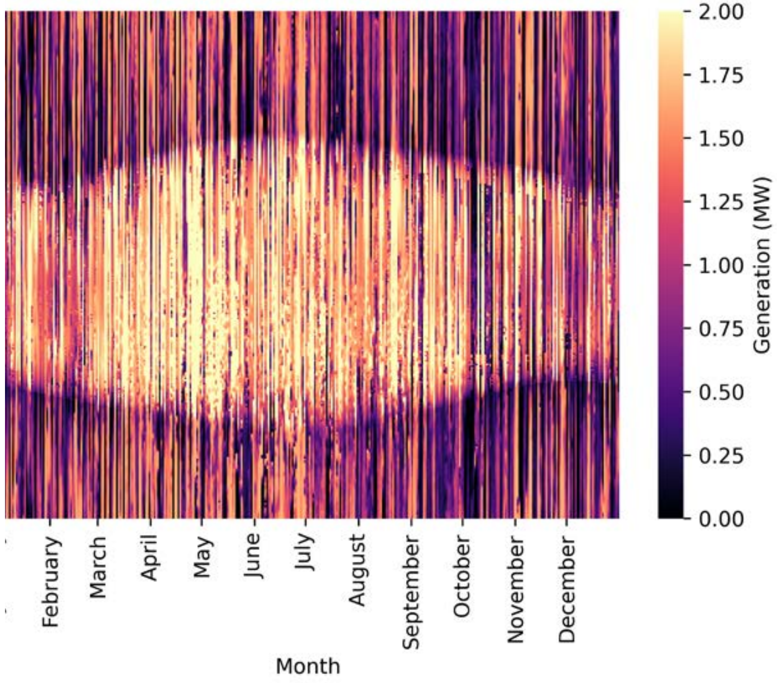
1 MW PV, Daggett, CA



1 MW wind, Casper, WY



1 MW wind + 1 MW PV, Amarillo, TX



Approach: Bottom-Up Manufacturing Cost Assessment Building Upon Previous Analysis

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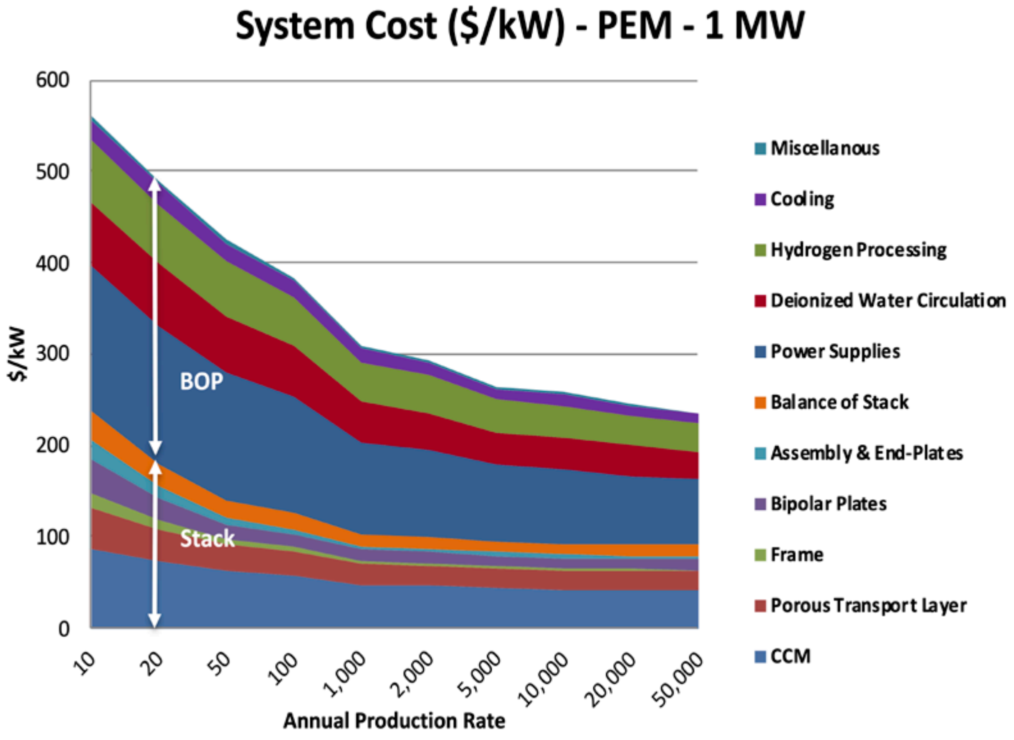
- Developing a bottom-up manufacturing cost model for the updated reference PEM system
- Adding manufacturing cost assessments of balance of plant (BOP) components – previous work involved only quotes for them
- Updating manufacturing processes and assumptions based on project team input

System Cost Estimate from Previous Analysis



Source: Mayyas, A., Ruth, M., Pivovar, B., Bender, G. & Wipke, K. Manufacturing Cost Analysis for Proton Exchange Membrane Water Electrolyzers. (2019).

Approach: Government Performance and Results Act (GPRA) Analysis

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- Conduct analysis consistent with objectives in FY22 GPRA Q1 milestone, meeting the following:

"Using the baseline PEM electrolyzer system model and the H2A Model, quantify at least three distinct pathways based on improvements to system cost, manufacturing, performance, and lifetime needed to achieve the H2 production cost targets of \$3.60/kg and \$3.10/kg by end of FY22 and FY23, respectively."

- Approach: Use H2A to map pathways to cost targets as a function of key economic inputs

- Capacity factor – fixed
- Electricity price – fixed
- **Capital cost**
- **Efficiency**
- **Lifetime**

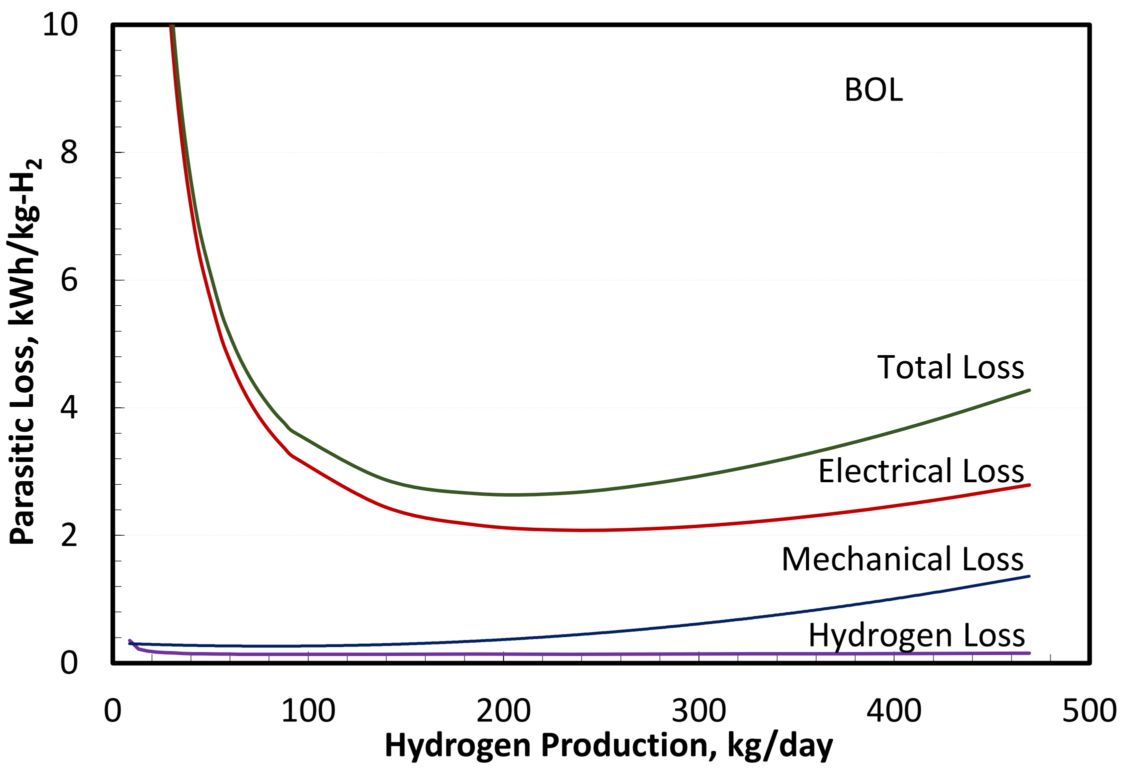
Parameter	GPRA baseline value	Units
Capacity factor	90%	%
Electricity price	0.03	\$/kWh
Stack efficiency	50.8	kWh/kg H2
System efficiency (LHV)	66.6 (50% LHV)	kWh/kg H2 (% LHV)
Replacement lifetime	40,000	hours
Estimated replacement cost	15%	% of direct capital cost

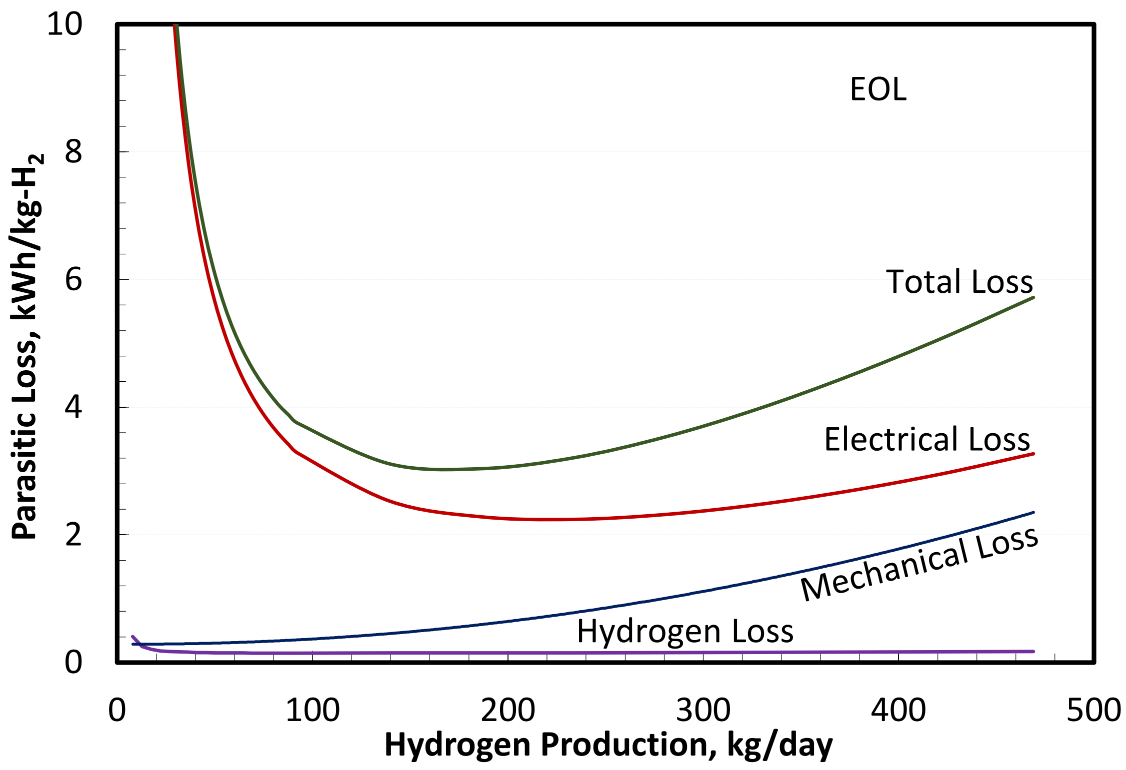
Accomplishment: Electrolysis System Models Predict Parasitic Losses and Identify Optimum Operating Conditions

Ranking of parasitic losses: electrical > mechanical > hydrogen

- Electrical losses: transformer/rectifier (95% efficiency at rated power decreasing to 90% at 10% power)
- Mechanical losses: pumps, radiator fan, chillers, recirculation blower, TSA electrical heater
- Hydrogen losses: H_2 crossover from cathode, H_2 dissolution in water

All data in kWh/kg-H_2	At Rated Power		At Minimum Loss	
	BOL	EOL	BOL	EOL
Electrical Loss	2.8	3.3	2.2	2.3
Mechanical Loss	1.3	2.3	0.4	0.6
Hydrogen Loss	0.2	0.2	0.1	0.1
Total	4.3	5.7	2.7	3.0





Accomplishment: Models Determine System Performance and Degradation

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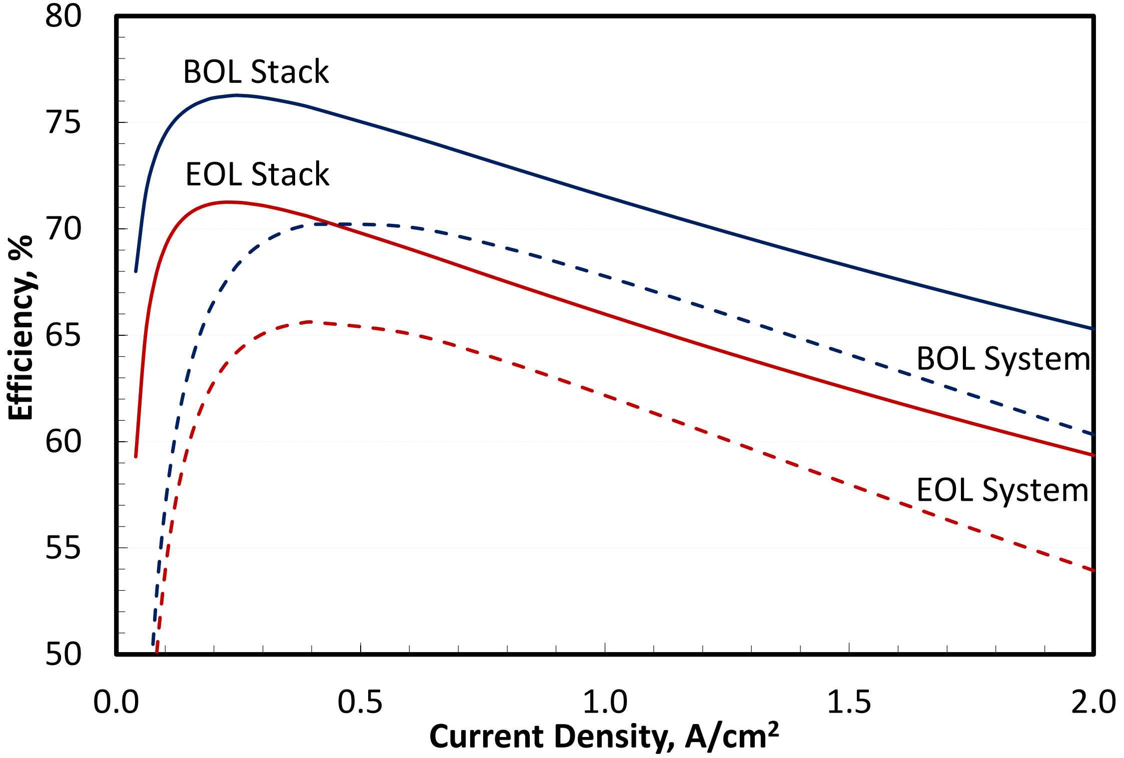
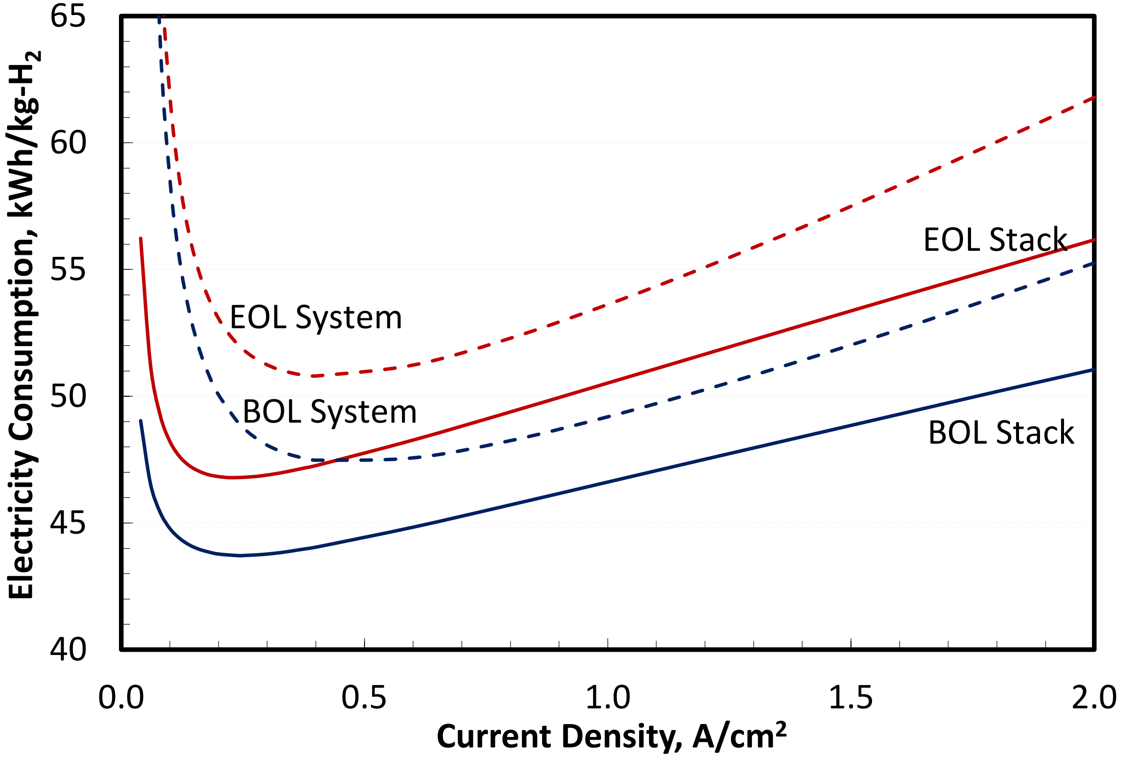
Efficiency Definitions

- Stack efficiency: LHV of net H_2 produced in the cathode divided by stack input power
- System efficiency: LHV of H_2 supplied to the pipeline divided by the total electrical power supplied to the transformer/rectifier and other BOP components

	Efficiency (%)		Efficiency (kWh/kg-H_2)	
	BOL	EOL	BOL	EOL
Stack				
Rated Power Efficiency	65.3	59.3	51.1	56.2
Peak Efficiency	76.3	71.2	43.7	46.8
System				
Rated Power Efficiency	60.3	53.9	55.3	61.8
Peak Efficiency	70.2	65.6	47.5	50.8





Accomplishment: Models Contextualize Advances in Cell Components and Quantify Remaining Progress Needed To Achieve DOE Targets

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MEMBRANE

Status

- N117 with Pt interlayer, N116(c) + N211(a)

N2025

- 60% lower HFR (membrane + contact) than N117
- A 125-µm (5-mil) thick N2025 will need to have 80% higher conductivity and 30% lower H_2 permeability than the N115 membrane

N2030

- 80% lower HFR than N117
- A 50-µm (2-mil) thick N2030 will need to have 90% higher conductivity and 70% lower H_2 permeability than the N212 membrane

OER CATALYST

Status

- Supported IrO_2/TiO_2 catalyst, 53 A/g_{Ir} OER activity

C2025

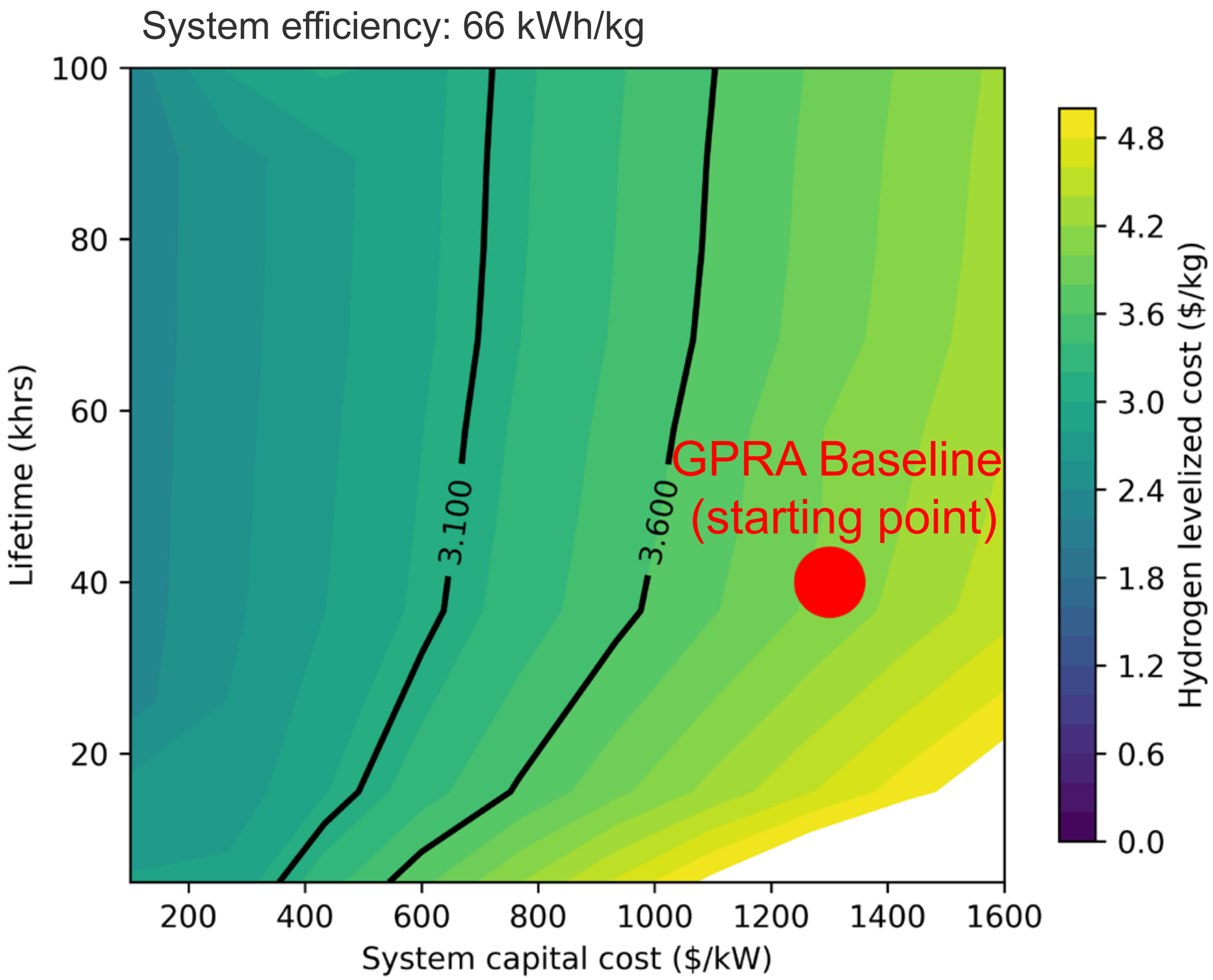
- 100 A/g_{Ir} OER activity, 20-30% higher than the activity of unsupported IrO_2 powder

C2030

- 2X C2025 OER activity

Parameter/Target	Units	Status	Interim Target	Ultimate Target
Stack Power	MW	1	3	3
Stack Hydrogen Production Rate	kg/d	469	1489	1576
Membrane		N117 Mitigated	N2025	N2030
Pt Loading in Membrane	mg-Pt/cm^2	0.025	0.025	0.01
Anode Catalyst		IrO_2/TiO_2	IrO_2	C2030
PGM Loading in Anode Catalyst	mg-Ir/cm^2	2	0.4	0.2
Cathode Catalyst		Pt/C	Pt/C	Pt/C
PGM Loading in Cathode Catalyst	mg-Pt/cm^2	1	0.1	0.05
Anode Porous Transport Layer (PTL)		Sintered Ti	Sintered Ti	Sintered Ti
PGM Coating in Anode PTL	mg-Pt/cm^2			
Cathode Porous Transport Layer		Carbon Paper	Carbon Paper	Carbon Paper
Separator Plate		Titanium	Titanium	Titanium
PGM Coating on Separator Plate	mg-Pt/cm^2			
Outlet Pressure	psi (bar)	450 (30)	450 (30)	450 (30)
Temperature	°C	80	80	80
Current Density	A cm^{-2}	2	3	3
Cell Voltage	V	1.9	1.8	1.7
Stack Efficiency	%	65.3	69.2	73.2
Stack Electricity Consumption	kWh/kg-H_2	51.1	48.2	45.5
OER Activity at 1.45 V	A/g_{Ir}	53	100	200
Membrane Resistance	mΩ.cm^2	139	55	21
Contact Resistance	mΩ.cm^2	20	10	10
Hydrogen Crossover	mA/cm^2	21	21	21
Water Stoichiometry		183	132	80
Stack Degradation Rate	µV/h	3.2	2.25	1.6
Stack Lifetime	h	60,000	80,000	100,000
System Efficiency	%	60.3	64.2	68.4
System Electricity Consumption	kWh/kg-H_2	55.3	51.9	48.8

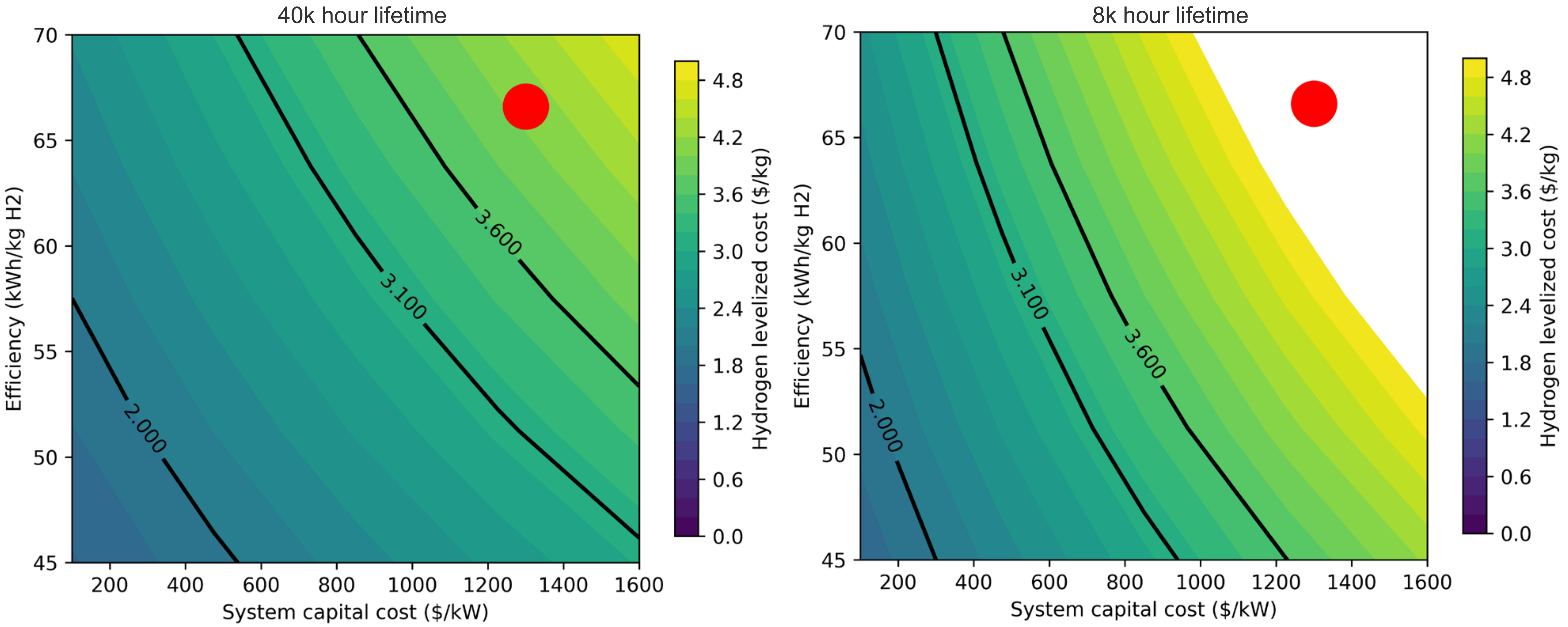
Accomplishment: GPRA Replacement Lifetime and Capital Cost Analysis



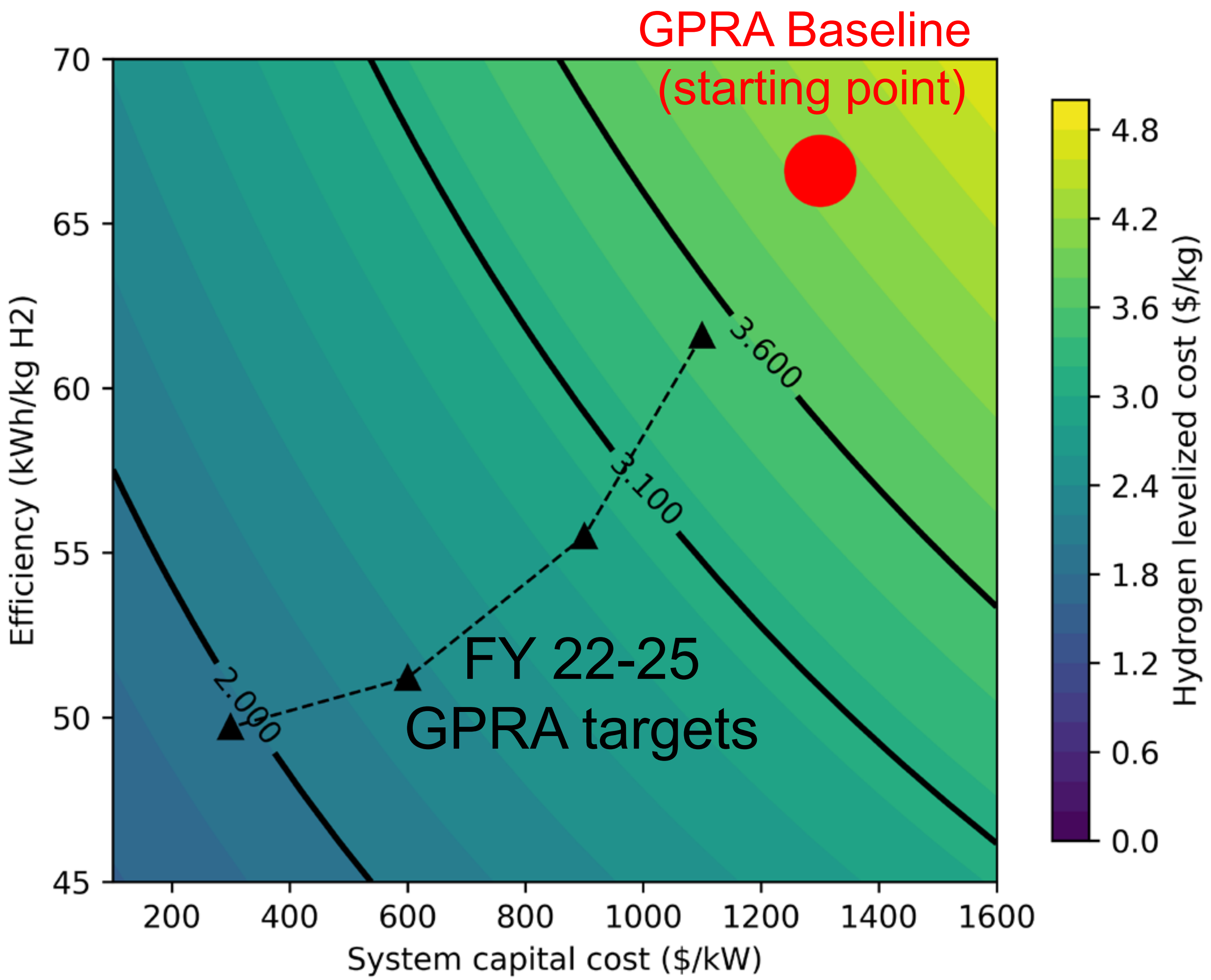
- Since the replacement cost is a function of direct capital cost, lower capital costs also drive the impact of system lifetime lower
- H2A approximates replacement costs as 15% of direct capital costs, which is a simplified representation of the true costs
- Low lifetimes (<20 khrs) can significantly impact economics

Accomplishment: System Lifetime/Durability GPRA Analysis

Advances in Performance and Cost cannot come at the Expense of System Lifetime/Durability



Accomplishment: Mapping possible GPRA pathways



- Between efficiency and capital cost, several possible paths exist to meet FY22 and FY23 GPRA targets
- Pathways could focus on advancing one parameter or a combination of both

Accomplishment: GPRA Target Pathways Matrix

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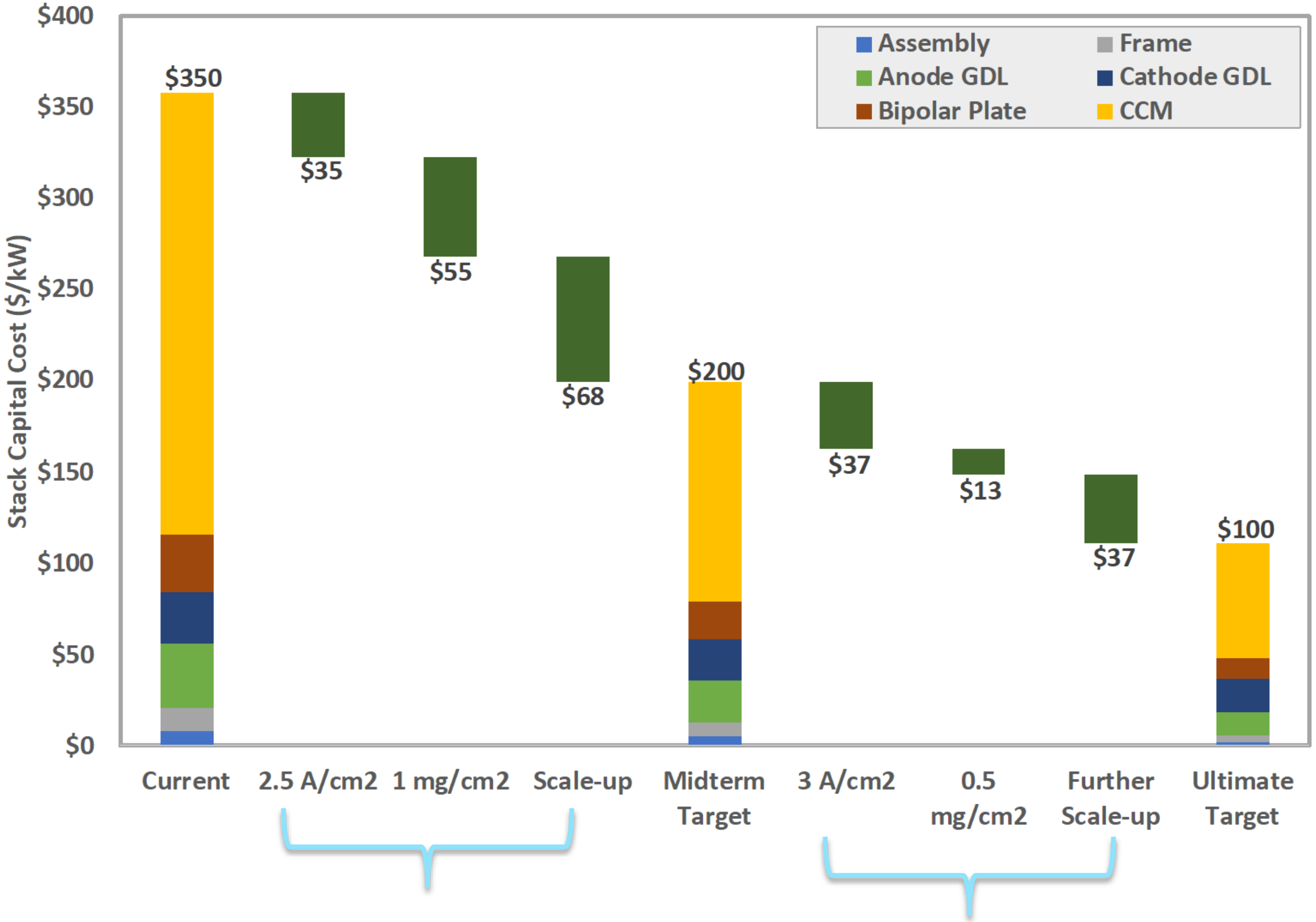
Electricity price: $0.03/kWh
Capacity factor: 90%

Cost target/year	Capital cost focus	Durability and efficiency focus	All of the above focus
$3.60 (2022)	$1,000/kW 66.6 kWh/kg 40 khrs	$1,250/kW 60 kWh/kg 40 khrs	$1,100/kW 61.6 kWh/kg 40 khrs
$3.10 (2023)	$850/kW 60 kWh/kg 40 khrs	$1,100/kW 57.5 kWh/kg 60 khrs	$900/kW 55.5 kWh/kg 50 khrs
$2.50 (2024)	$500/kW 60 kWh/kg 40 khrs	$800/kW 55 kWh/kg 80 khrs	$600/kW 51.2 kWh/kg 60 khrs
$2.00 (2025)	$200/kW 55 kWh/kg 40 khrs	$500/kW 47 kWh/kg 100 khrs	$300/kW 49.7 kWh/kg 80 khrs

Accomplishment: Analysis of Cost Drivers for PEM Stacks



Stack Targets	Status	2023	2025
Cell (A/cm^2@1.9V)	2.0	2.5	3.0
Efficiency (%)	66	68	70
Lifetime (khr)	60	70	80
Degradation (mV/khr)	3.2	2.75	2.25
Capital Cost ($/kW)	350	200	100
PGM loading (mg/cm^2)	3	1	0.5

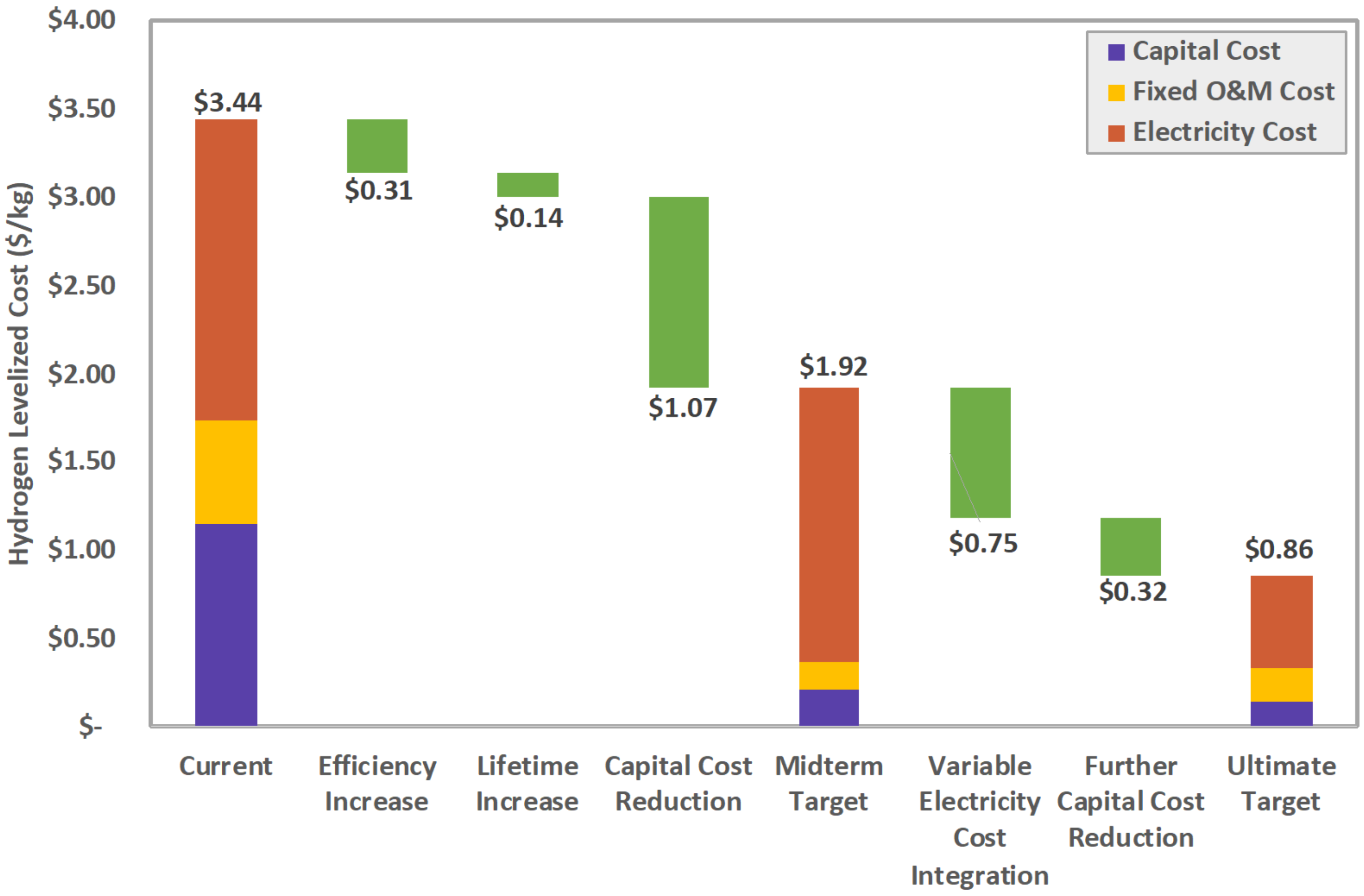
These 3 areas

1. Increased efficiency/current density
2. Decreased PGM loading
3. Scale-up

Are the strongest levers for addressing stack costs.

https://www.hydrogen.energy.gov/pdfs/review21/p196_pivovar_boardman_2021_o.pdf

Accomplishment: Analysis of Hydrogen Levelized Cost Drivers



- Select pathways to $2/kg and $1/kg identified.
- Much of HLC gains possible through greatly decreasing capital costs and enabling lower cost electricity through variable operation.
- These advances can't come with compromised durability or efficiency, so all three areas are linked.

https://www.hydrogen.energy.gov/pdfs/review21/p196_pivovar_boardman_2021_o.pdf

Accomplishment: Operating Cycles for Electrolyzers Operating in Wholesale Power Markets

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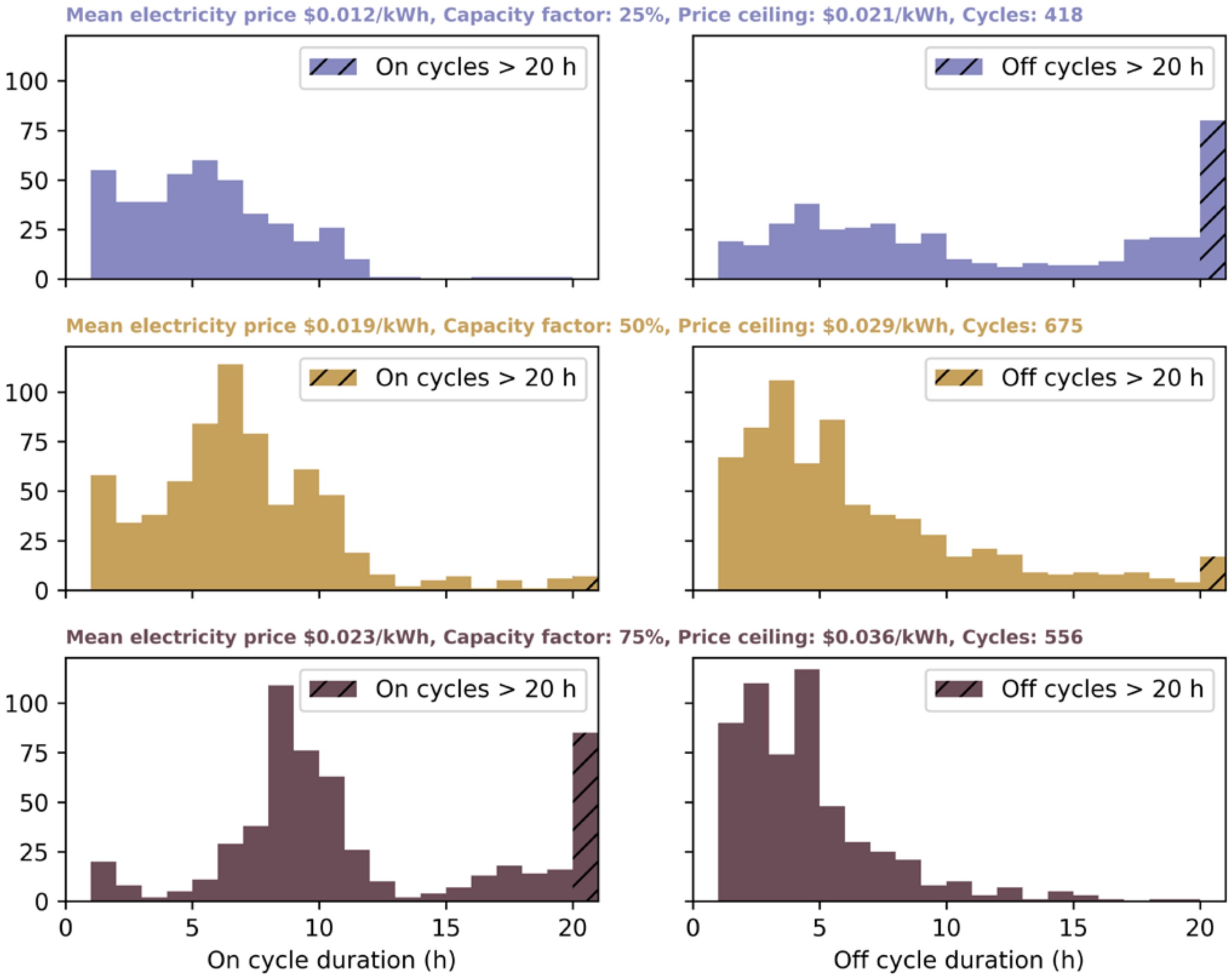
- Regular cycling is needed to minimize hydrogen levelized costs by operating during times of low wholesale electricity prices
- Optimal on/off cycling is likely at least once per day and may be twice per day
- Cycling will likely impact electrolyzer durability (especially with lower-cost electrolyzers).
- Operating cycle strategies will inform H2NEW Task 1 strategies and experimental results will impact hydrogen levelized costs

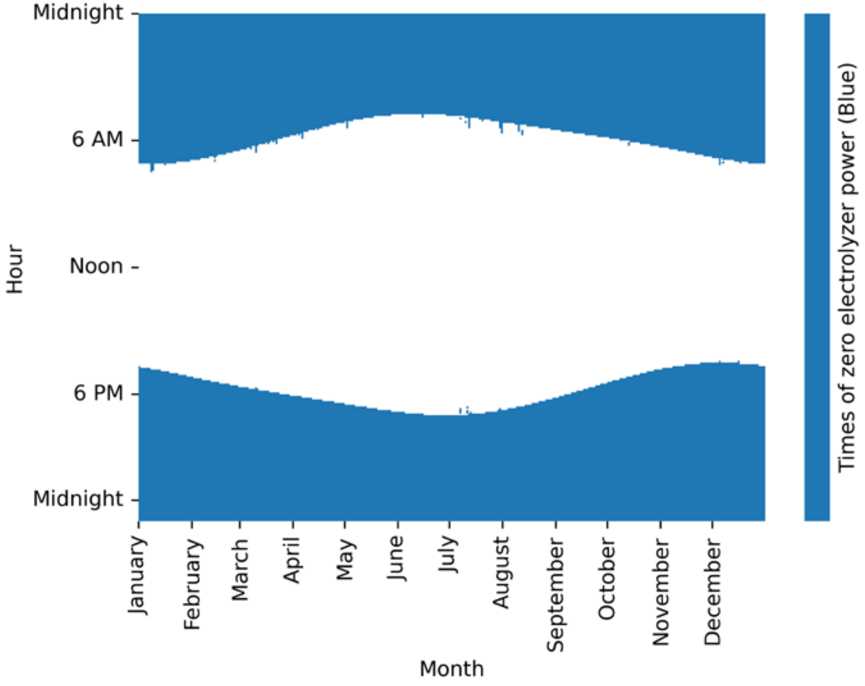


Badgett, A., M. Ruth, B. Pivovar. "Economic Considerations for Hydrogen Production with a Focus on Polymer Electrolyte Membrane Electrolysis" Submitted as a chapter in Hydrogen Production by Water Electrolysis. Ed. Tom Smolinka. April 9, 2021.

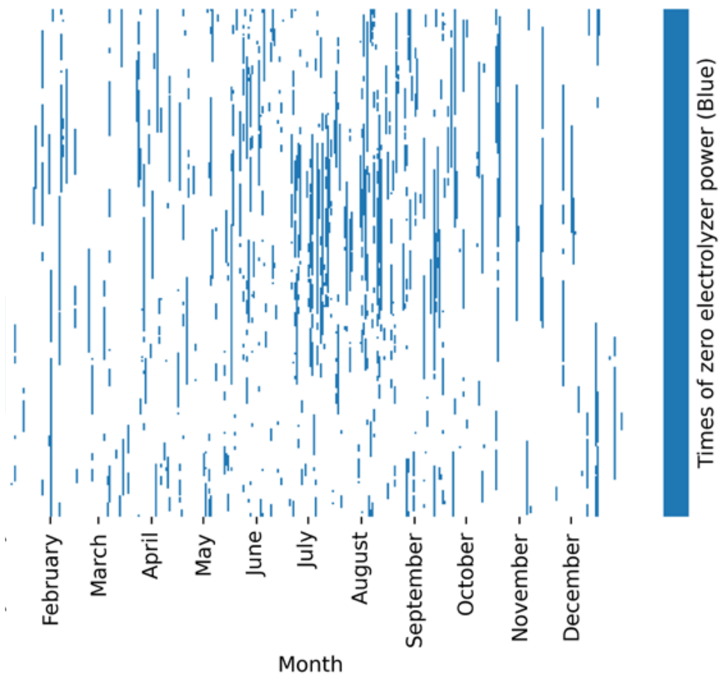
Accomplishment: Operating Cycles for Electrolyzers Coupled to Wind and/or Solar

- PV generation forces electrolyzer to shut off in evenings, while wind generation is more random but at a higher capacity factor
- Combining PV+wind hybridized systems could minimize electrolyzer on/off cycles and degradation
- Battery energy storage can also be paired with these systems to charge and discharge to minimize on/off cycles

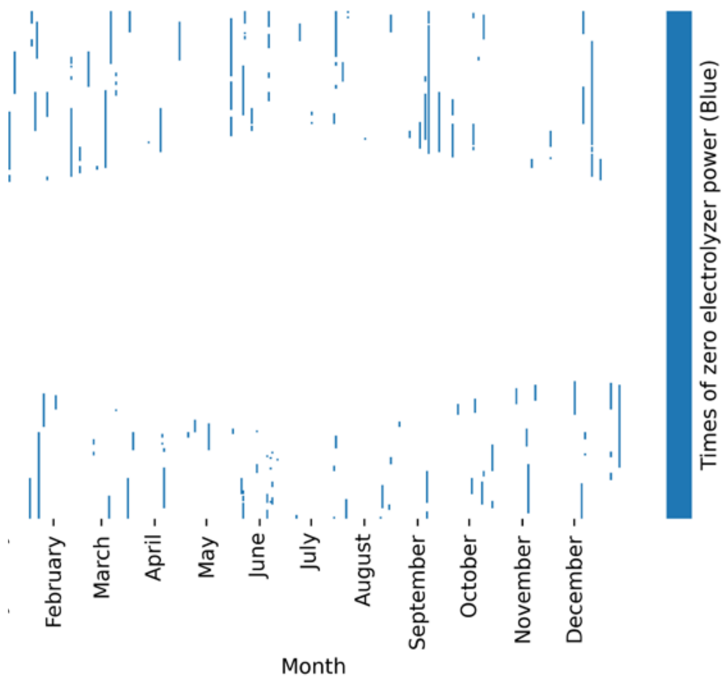
1 MW PV, Daggett, CA



1 MW wind, Casper, WY



1 MW wind + 1 MW PV, Amarillo, TX



Accomplishments: Responses to Previous Year Reviewers' Comments

- This project was not reviewed in the previous year

Collaboration and Coordination

- This task is being performed by two laboratories: NREL and ANL
- This task interacts with the rest of the H2NEW consortium which includes seven additional laboratories and has a steering team involving industrial partners. Interactions include getting design and operating input and data from consortium partners and informing R&D staff of operating cycles and other considerations.
- Designs and assumptions are reviewed by industrial and academic partners on the consortium's advisory committee.
- Designs and manufacturing assessments involve interactions with Strategic Analysis, Inc.

Remaining Challenges and Barriers

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- Impacts of degradation on technoeconomics have not been quantified
- Manufacturing costs are preliminary especially for key balance of plant components (e.g., power electronics)
- New designs, experimental results, and opportunities are being developed but their potential impact on overall performance and economics are unknown
- Electrolyzer end-of-life and recyclability and material circularity is unknown
- Potential benefits of direct coupling to renewables (e.g., PV-electrolyzer coupling without conversion to AC power) have not been finalized
- Impacts of adding a large number of electrolyzers to the grid on electricity prices are unknown

Proposed Future Work

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- Planned work during FY23
  - Finalize models for electrolyzers coupled to wholesale power markets and renewable power generation
  - Improve manufacturing cost model to capture current knowledge and improve estimates for key components (e.g., power electronics)
  - Develop estimates for system capital costs when directly connected to renewable generation
  - Add durability factors to performance models and economic models and quantify impacts of degradation on economics
- Planned work during outyears
  - Work with researchers to identify options and implement them in the models for use in comparisons and providing feedback to researchers
  - Adapt models to identify component reductions and potential benefits of direct coupling to renewables
  - Develop and perform price-maker analyses to quantify potential impacts of increased loads on electricity generation and prices

Proposed future work is subject to change based on funding levels.

Summary

- Performance, manufacturing, and system analysis is underway and tools are being developed and implemented
- Results will be used to evaluate cost, performance, and durability tradeoffs to determine optimum LTE deployment to achieve $2/kg and $1/kg production cost in renewable energy integration scenarios
- Operating pressure, temperature, and membrane properties are key considerations
- Low price electricity can be sourced from wholesale power markets or by direct connection to renewable power generation
- Tradeoffs between using low-price electricity and cycling are a key consideration while developing operating strategies and durability objectives
- Interactions with others in H2NEW lead to improved analysis and provide opportunities for analysis results to guide research and target setting

Thank You!

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NREL/PR-6A20-82706

Supporting Slides

Technology Transfer Activities

- This analysis provides context for technology transfer across H2NEW
- No additional specific technology transfer is occurring in this task

Progress Toward DOE Targets

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- This task is quantifying progress of H2NEW toward DOE's $2/kg and $1/kg production target.

Publications and Presentations

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- Badgett, A., Ruth, M. and Pivovar, B. (2022) 'Chapter 10 - Economic considerations for hydrogen production with a focus on polymer electrolyte membrane electrolysis', in Smolinka, T. and Garche, J. (eds) *Electrochemical Power Sources: Fundamentals, Systems, and Applications*. Elsevier, pp. 327–364. doi: https://doi.org/10.1016/B978-0-12-819424-9.00005-7.
- Badgett, A. *et al.* (2021) 'Methods identifying cost reduction potential for water electrolysis systems', *Current Opinion in Chemical Engineering*, 33, p. 100714. doi: 10.1016/j.coche.2021.100714.

Key Assumptions and Knowledge Gaps for Technoeconomic Calculations in this Presentation

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Assumption	Notes
Wholesale electricity market access	In the electricity price analyses shown here, we have assumed that electrolyzers will have access to wholesale electricity priced at hourly intervals. This access enables lower hydrogen costs through operation as a dispatchable load, however electrolyzers do not currently operate in this manner and those electricity markets are not regularly available to them at this time. We have discussed this with regard to the benefits that electrolysis that can offer as a dispatchable, scalable resource providing benefits in capacity and economic return. Areas of opportunity include connecting the electricity market more strongly to transportation and industrial sectors, offering capacity and seasonal storage options beyond other traditional storage pathways, accessing markets beyond grid to grid, and allowing for one way storage removing energy from the electricity sector that doesn't need to be returned to the grid. However, regulations that allow access to wholesale markets or having electrolyzers deployed behind the meter will likely be critical for economically competitive HLC.
Electrolyzer durability, performance, and cost	Most of the H2A analysis inputs explored in this work either assumed that the efficiency of the device was constant over its operation or achieved a high net average efficiency of operation (66% efficiency). This assumption was made regardless of the cost of the electrolysis system or the manner in which it was operated. The only caveat to this is that each electrolysis system modeled had the same number of calendar hours of operation, basically assuming that dispatchable operation has the same impact as a different number of operating hours, or any impacts of operating dynamically. The research community has demonstrated that operating strategy impacts the durability of electrolysis systems, and the exact tradeoff between operating strategy and degradation has emerged as a critical research area. Based on past durability of PEM electrolyzers and the performance of PEM fuel cells systems, it has been proposed that operating strategies can be developed that meet combined cost, performance and durability targets for PEM electrolyzers, but meeting durability requirements or achieving cost reductions while maintaining required performance levels remains an area of scientific uncertainty and is being actively investigated.
Fixed O&M costs	Fixed annual O&M costs within this Chapter were estimated using H2A default assumptions (a fixed percentage of installed capital costs) and did not vary with the number of hours the system was assumed to be operated annually or the manner in which it was operated. O&M costs are unlikely to be a fixed percentage of capital costs. Rather, they are likely to depend significantly on how systems are operated. Testing and operational strategy development are needed to better estimate O&M costs and under what circumstances they become critical to HLC.
Evolution of electricity markets including impact of electrolyzers	In a number of the analyses presented, historical LMPs were used to illustrate how HLC could be optimized with different electrolyzer deployment strategies. In general, the costs for wholesale electricity have been decreasing and becoming more variable. That combination increases the value proposition of flexible loads like electrolyzers because they can support balancing electricity generation and load. Costs of balancing generation and load are likely to increase as variable renewable energy penetration further increases. These trends do not guarantee what the future electricity markets will be and none of the analysis performed in this Chapter attempted to capture the potential impact that large scale electrolysis (or other energy storage options) might have on wholesale electricity markets. These are complicated interactions that are likely to evolve considerably in the coming years.
Renewables deployment	Many of the emerging challenges to the electric sector are being driven by the improving economics and increased deployment of renewable energy. Renewable energy is increasing in deployment through a combination of economic factors and other policy or legislative actions. As renewable penetration increases, technologies like electrolysis can provide benefits by enabling large scale energy storage over seasonal durations creating opportunities for increased value of wind and solar resources. There is a synergy between electrolysis and renewable energy deployment that allows each to make the other more economical, but often deployment of renewable energy is not done solely on an economic basis, and electrolyzers can benefit from increasing renewable deployment.
Policy drivers/ legislative actions	Policy is a powerful tool that can either support or discourage further development of electrolysis. It can incentivize electrolysis deployment directly by applying to the electrolyzer itself or indirectly by applying to other factors that influence electrolysis. Those other factors could include increasing variable renewable electricity generation, enabling access to wholesale electricity rates, and through other economic drivers such as costs on different emissions. While the analyses conducted here do not consider the effects of any future policy mechanisms, we acknowledge the importance of such mechanisms to influence deployment of electrolysis.
Hydrogen storage and transmission	None of the work presented in this Chapter focused on the significant challenges of hydrogen storage and transmission and the costs associated with these challenges. In order to advance electrolysis technology and ensure that low HLC availability has broad impact, both hydrogen storage and transmission need advances in parallel. In addition, hydrogen distribution for smaller-scale demand nodes (e.g., fueling stations) need advances for those markets to grow.