

# H<sub>2</sub>NEW: Hydrogen (H<sub>2</sub>) from Next-generation Electrolyzers of Water LTE Task 3c: System and Technoeconomic Analysis

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DOE Hydrogen Program

2023 Annual Merit Review and Peer Evaluation Meeting

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Project ID # P196D

# Task 3c team members



Bryan Pivovar (NREL):  
H2NEW director, subtask co-lead



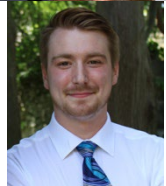
Alex Badgett (NREL):  
Subtask co-lead



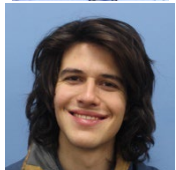
Joe Brauch (NREL):  
Electricity supply modeling



Lauren Sittler (NREL):  
Discounted cash flow analysis



Chris Skangos (NREL):  
Manufacturing analysis



Colby Smith (NREL):  
Liquid alkaline modeling



Rajesh Ahluwalia (ANL):  
Performance modeling lead



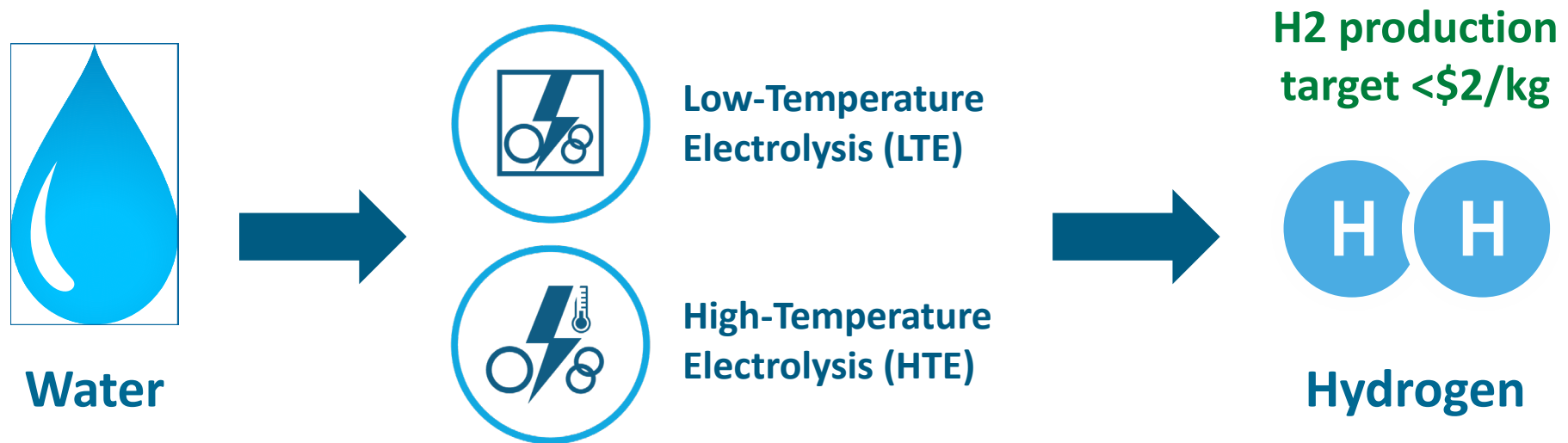
Xiaohua Wang (ANL):  
Performance and durability  
model development

Dionissios Papadias (ANL):  
Life cycle analysis

Luke Johnson (ANL):  
Performance modeling

Samuel Kazmouz (ANL):  
Performance modeling

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

## Timeline and Budget

- Project start date: 10/1/2021
- FY21 DOE funding: \$400K (\$275K NREL and \$125K ANL)
- FY22 DOE funding: \$400K (\$275K NREL and \$125K ANL)
- FY23 planned DOE funding: \$900K (\$550K NREL and \$350K ANL)

## Barriers/targets

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

## Partners

- Project lead: Bryan Pivovar (NREL)
- Task Leads: Rajesh Ahluwalia (ANL) and Alex Badgett (NREL)

- 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 and operations 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

# Interfaces between H2NEW research areas and hydrogen levelized cost targets

## H2NEW task 3c activities

Technoeconomic cost modeling

Electricity market analysis

Systems analysis

## Key hydrogen levelized cost factors

Electrolyzer capital cost

Electricity price and operating strategy

Performance and durability



1 Dollar



1 Kilogram

**Hydrogen levelized cost \$/kg H<sub>2</sub>**

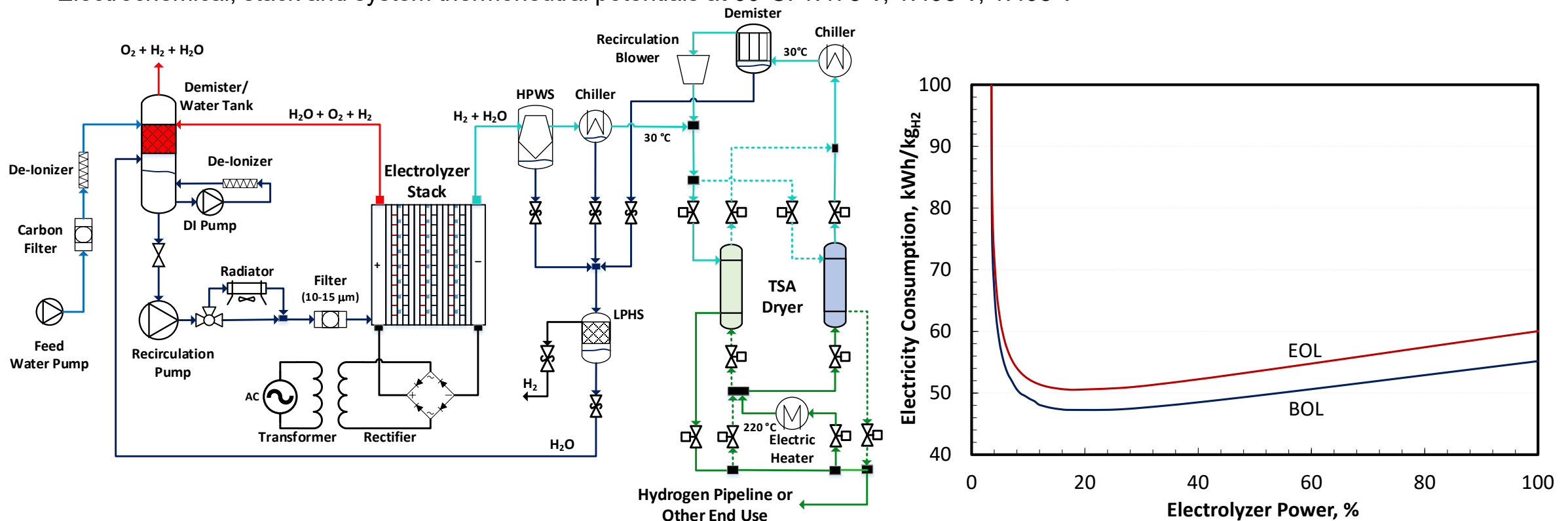
Experimental R&D

## EOL specific energy consumption (SEC) based on 10% increase in beginning of life (BOL) cell voltage at rated power

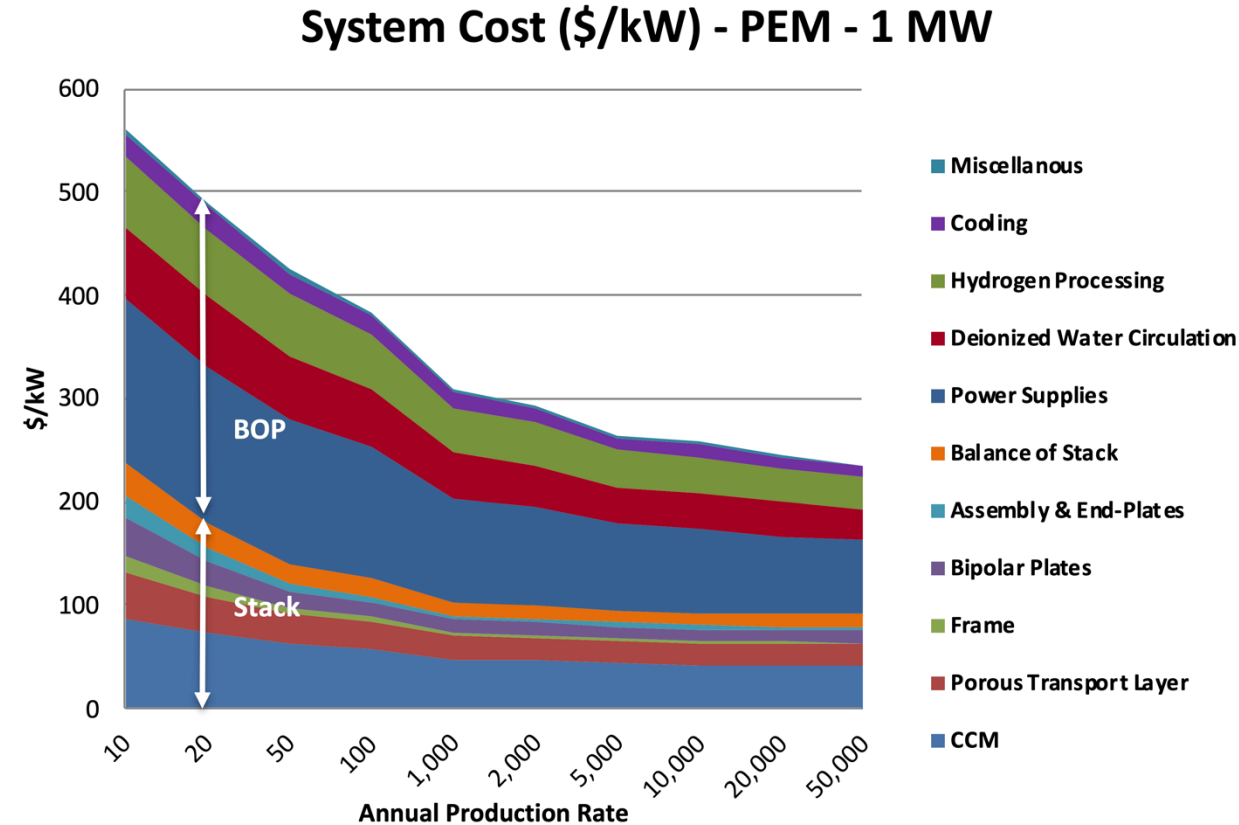
- Ranking of parasitic losses: mechanical > electrical > hydrogen
- SEC at rated power: 55.2 kWh/kg-H<sub>2</sub> at BOL, 61.5 kWh/kg-H<sub>2</sub> at end of life (EOL)
- Minimum SEC: 47.3 kWh/kg-H<sub>2</sub> at BOL, 50.5 kWh/kg-H<sub>2</sub> at EOL

## System turndown determined by lower flammability limit (LFL) rather than thermoneutral potentials

- Minimum system power with mitigated membrane: 3.5%
- Electrochemical, stack and system thermoneutral potentials at 60°C: 1.475 V, 1.493 V, 1.498 V



- Building on previous analysis findings:
  - Electrolysis system costs are driven by material requirements and balance of system equipment
- Cost drivers and areas for model updates and refinement:
  - Lower catalyst loadings
  - Manufacturing economies of scale
  - Balance of plant equipment and integration



Mayyas et al., 2018. NREL/TP-6A20-72740.  
<https://www.nrel.gov/docs/fy19osti/72740.pdf>

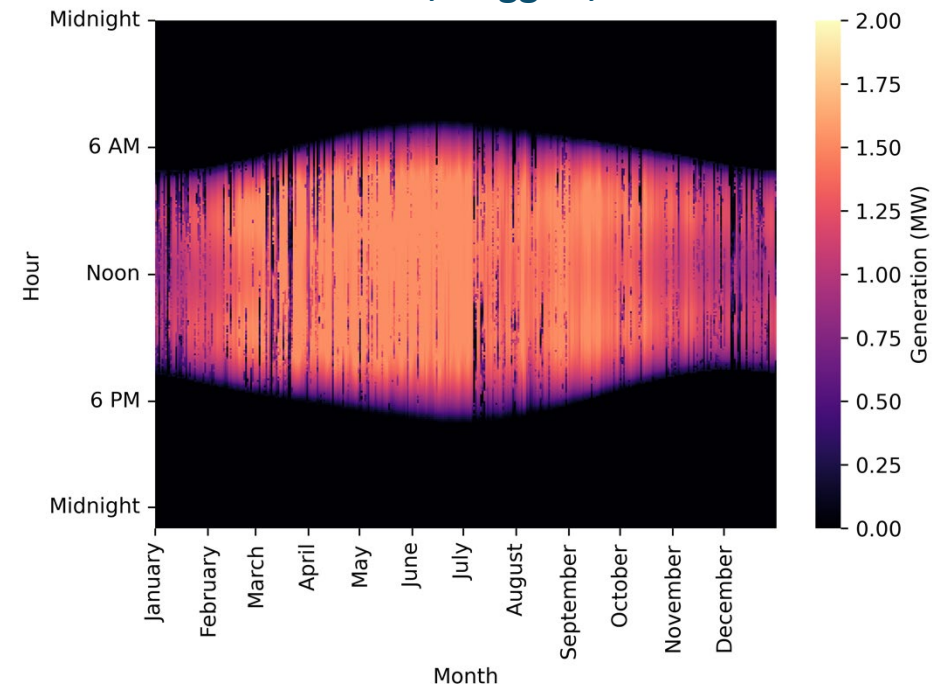


- Hydrogen production analysis models (H2A) standardize assumptions and provide a basis for mapping the impact of efforts underway in H2NEW on hydrogen levelized cost (HLC)
- Previous H2A analysis assumed constant electrolyzer efficiency at various operating setpoints and no degradation in efficiency as stack approaches its end of life
- Connecting stack replacement costs with degradation rates and electrolyzer operating profile provides a realistic representation of the economics of electrolyzer operation
- Updated analysis framework leverages the H2A-Lite model



**H2A**

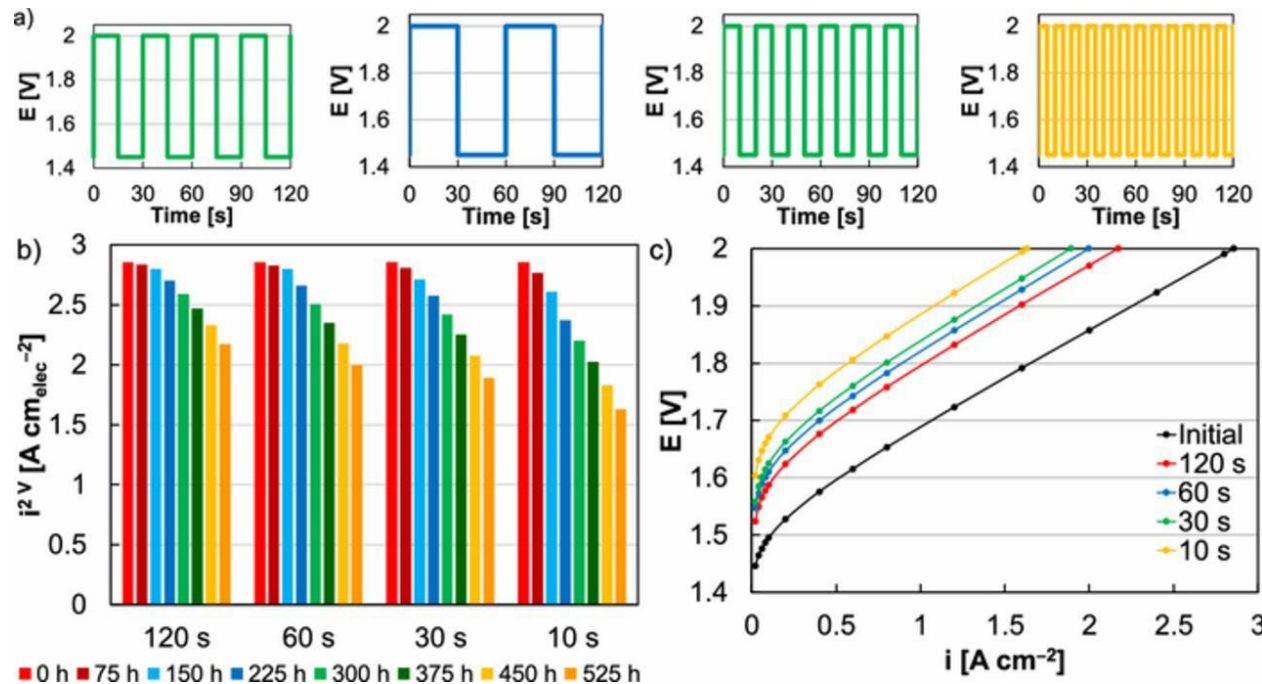
**1 MW PV, Daggett, CA**



# Accomplishment: Experimental data to inform cost optimization

- Leverage H2NEW experimental activities to inform tradeoffs between electrolyzer design over the system lifetime
- Ongoing effort focusing on mapping electrolyzer performance degradation to dynamic operating cycles, better coupling performance modeling, experimental data, and TEA

Overall decay  $\rightarrow \Delta\eta = \underbrace{\left(\frac{\partial\eta}{\partial t}\right)}_{\text{Decay from steady state operation}} + \underbrace{\left(\frac{\partial\eta}{\partial c}\right)}_{\text{Decay from cycling}} + \underbrace{\left(\frac{\partial\eta}{\partial s}\right)}_{\text{Decay from startup-shutdown}}$

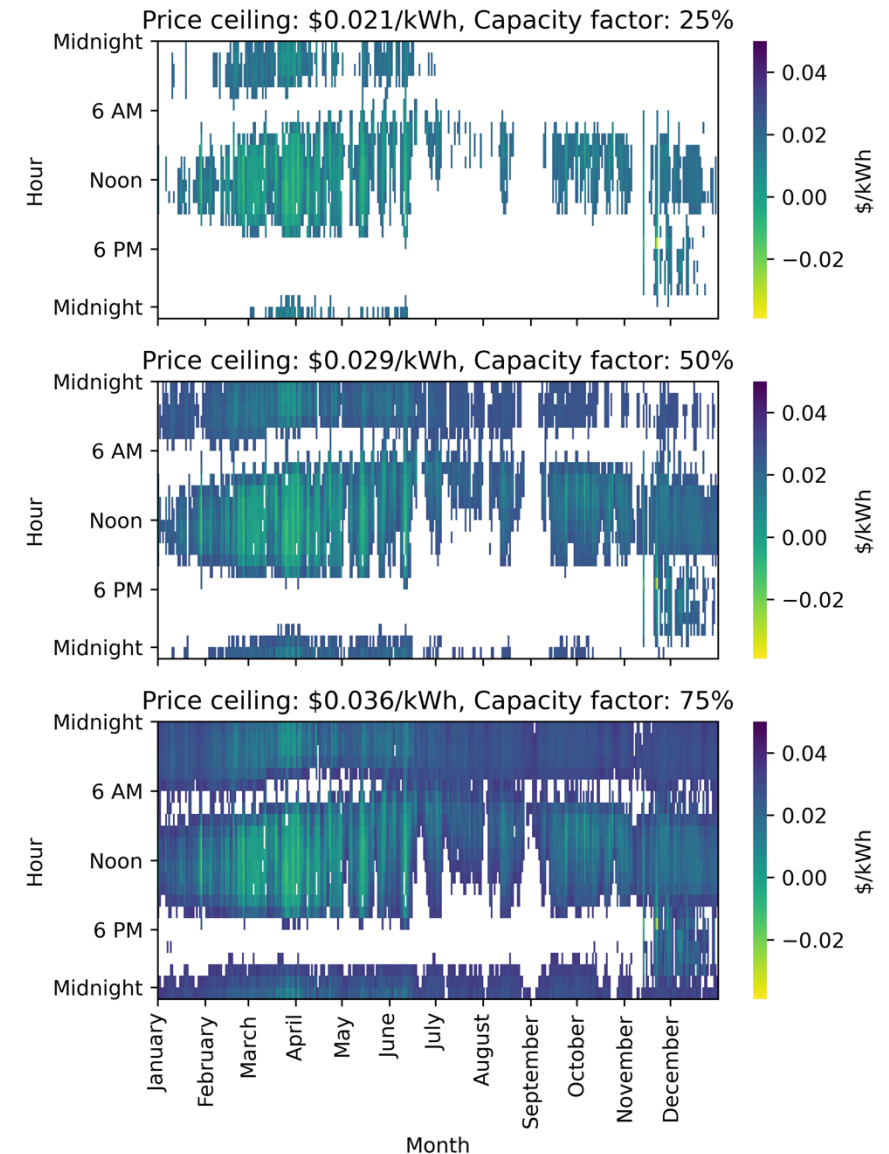


Shaun M. Alia et al 2019 J. Electrochem. Soc. 166 F1164

# Accomplishment: Updated manufactured cost analysis for PEM electrolyzers

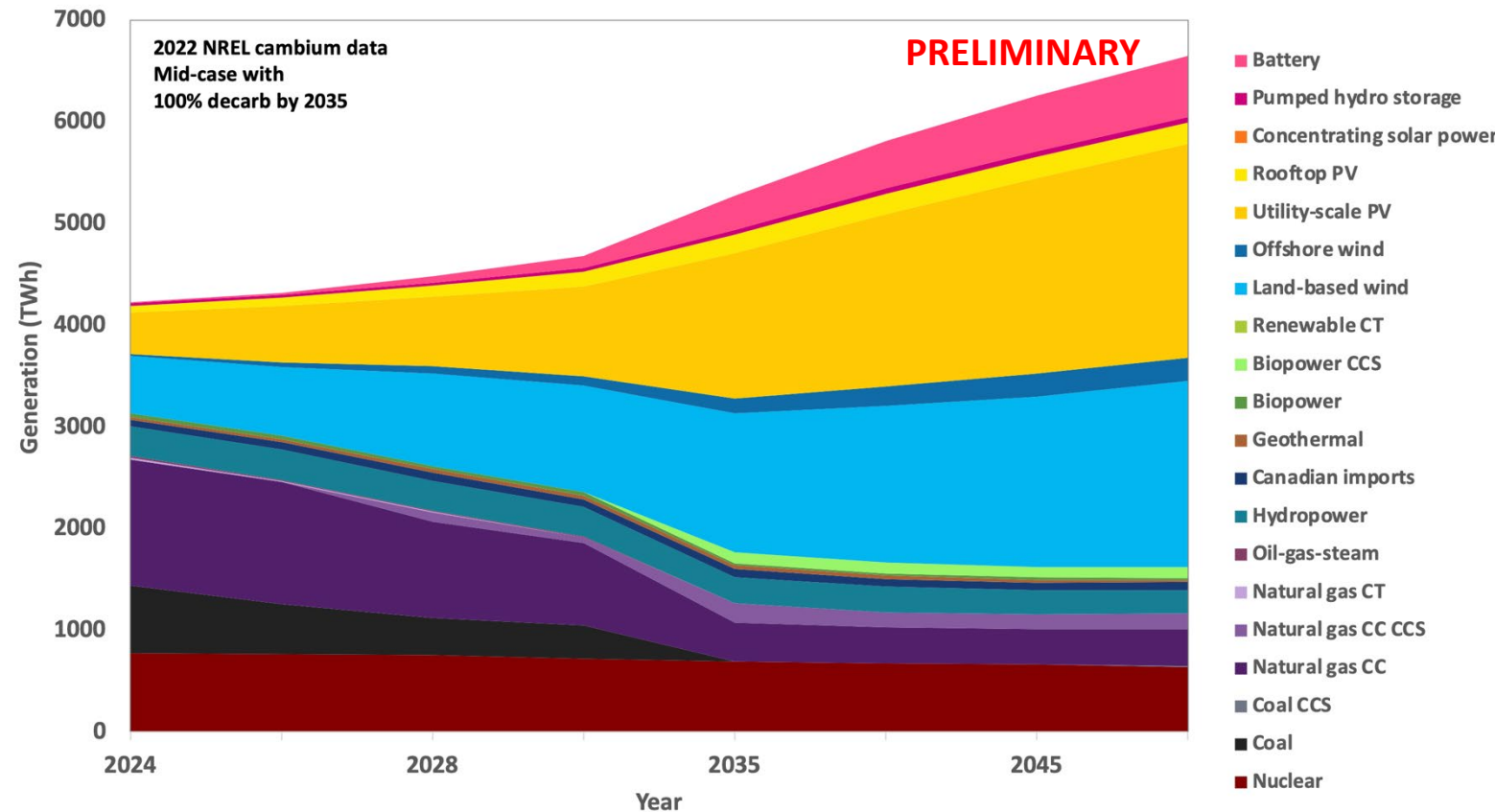
- Completed updated manufacturing cost modeling for PEM electrolyzers, including updates to many BOP components for more accurate sizing and cost estimation
- Electrolyzer stack and BOP both contribute significantly to total costs
- Stack costs are dominated by catalyst material (namely iridium) costs, especially at high manufacturing scales
  - Reduction of expensive material via decreased loading, increased current density, alternative materials, etc. could be a promising pathway for capital cost reduction, but may have trade-offs with degradation
- BOP costs are divided roughly evenly among subprocesses, but electrical BOP and hydrogen processing (drying) are the most significant contributors
  - Cost reduction could be achieved via electrical BOP optimization (e.g., direct connection to renewables) or end use optimization to lower purity/drying requirements
  - Hydrogen processing is expensive at pressure (30 bar); reducing pressure could also lower costs, but may come with other performance trade-offs
- High-throughput manufacturing and experiential learning for BOP will be critical to reducing costs at scale
- Report outlining conclusions from this analysis is under preparation

- Completed work has considered:
  - Historical location marginal prices for electricity in wholesale power markets in California ISO, Palo Verde node
  - Modeling of standalone renewable connection with wind and solar and associated operating strategies
  - Analysis of electrolyzer duty cycles associated with various integration strategies, quantifying annual startup/shutdowns
- Approach for ongoing work considers:
  - Turndown ratios to avoid startup/shutdown cycling
  - Future looking cost projections for power sector buildout scenarios
  - Spatial variation in prices and operating strategy
  - Findings from coupling experimental data on electrolyzer degradation



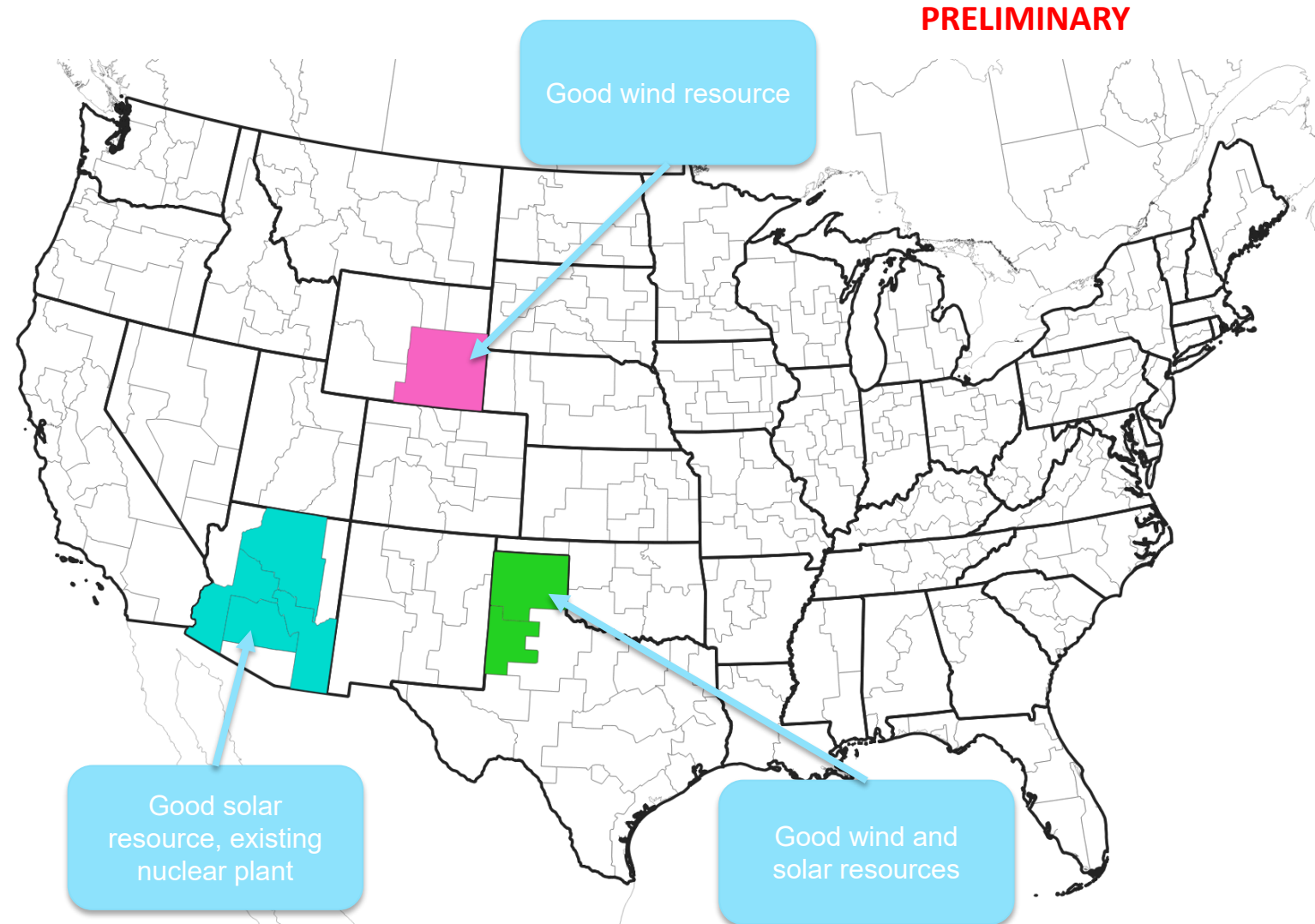
# Status/Approach: Increased renewable deployment and implications for electrolysis

- As increased variable renewables are deployed onto the grid, the wholesale cost of energy on an hourly basis is likely to become more volatile
- Wholesale power markets are likely to see higher numbers of hours when the marginal cost of energy is low or zero



# Status/Approach: Mapping opportunities for low marginal cost electricity

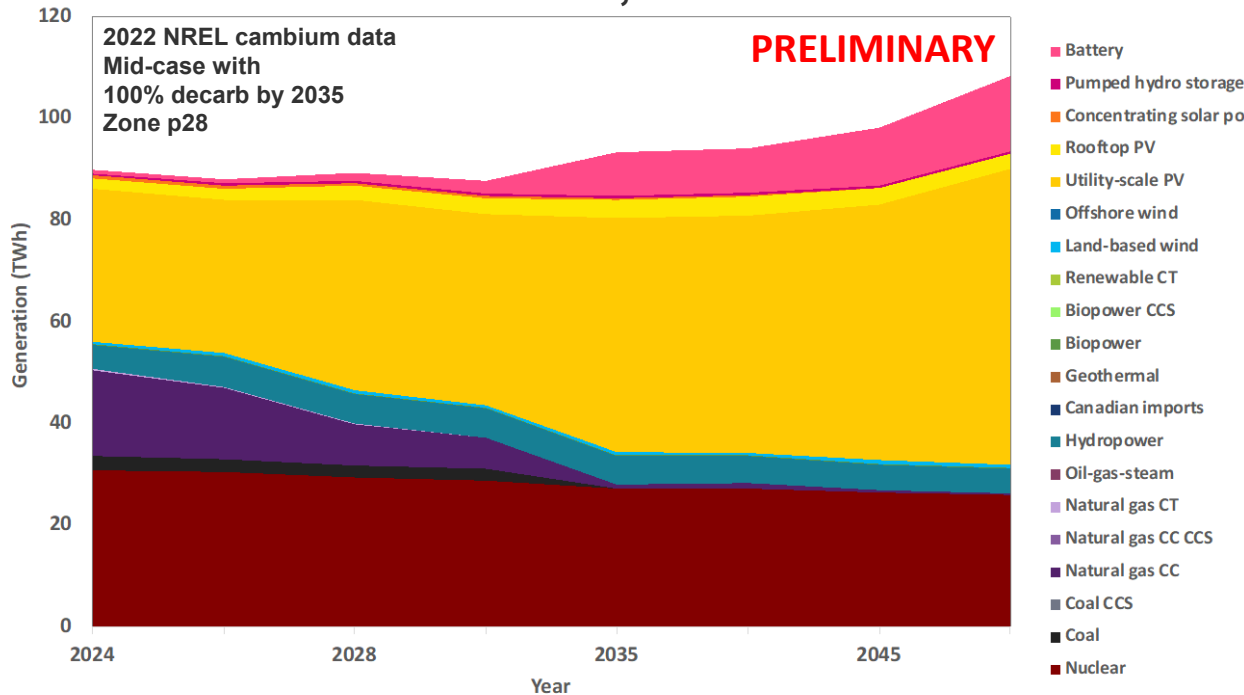
- The hourly marginal cost of energy in a location can depend on:
  - Renewable resources
  - Electricity load profiles and magnitude of demand
  - Existing generation
  - Transmission lines



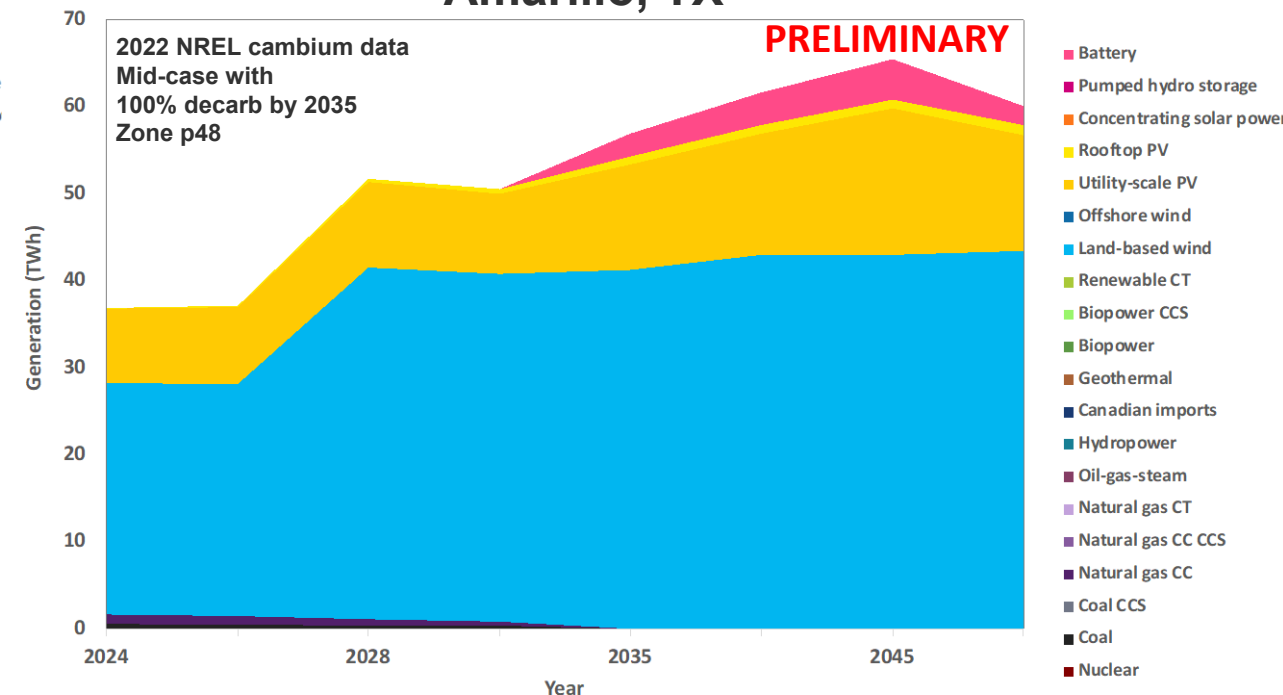
# Status/Approach: Regional variation in optimized resource mix

- The lowest-cost solution to enable grid decarbonization by 2035 results in mixed generation technologies from location to location
- This spatial variance drives the hourly cost of energy in these locations, creating different opportunities for electrolyzers to minimize the cost of H2

**Palo Verde, AZ**



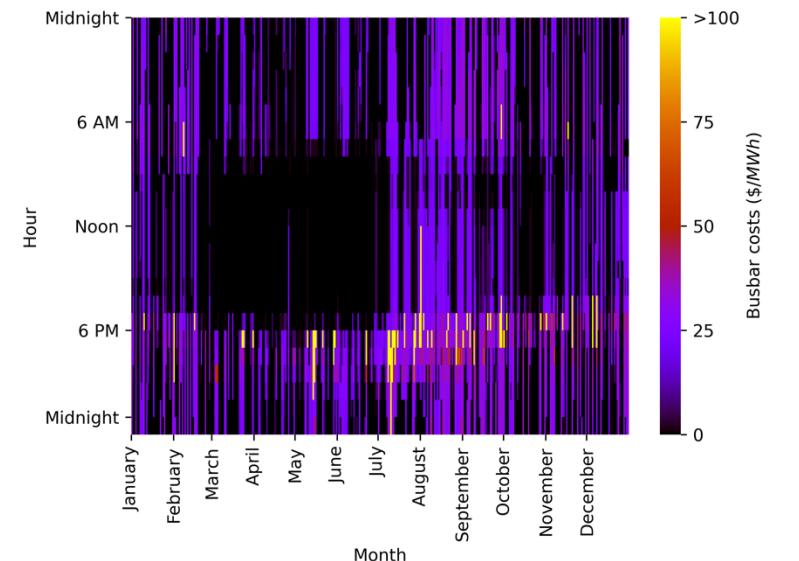
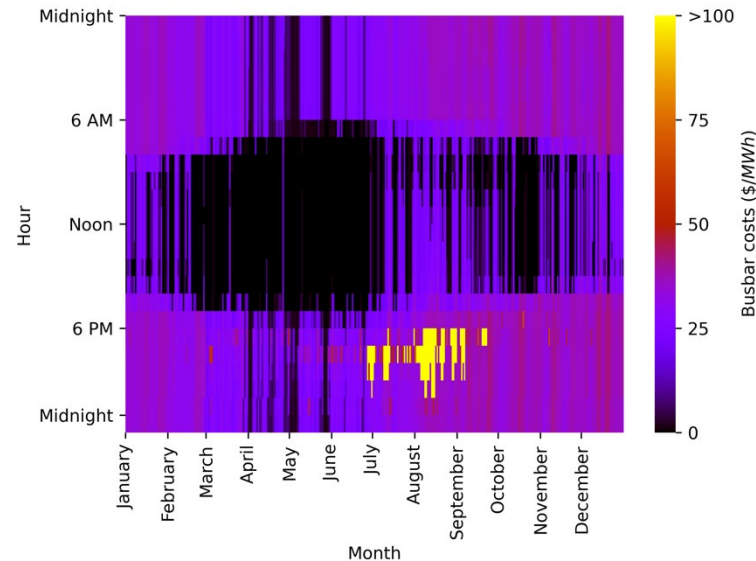
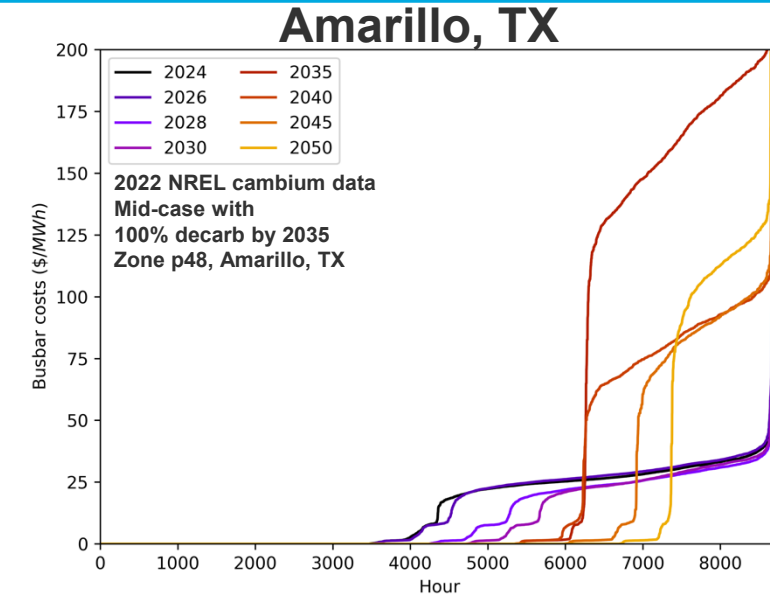
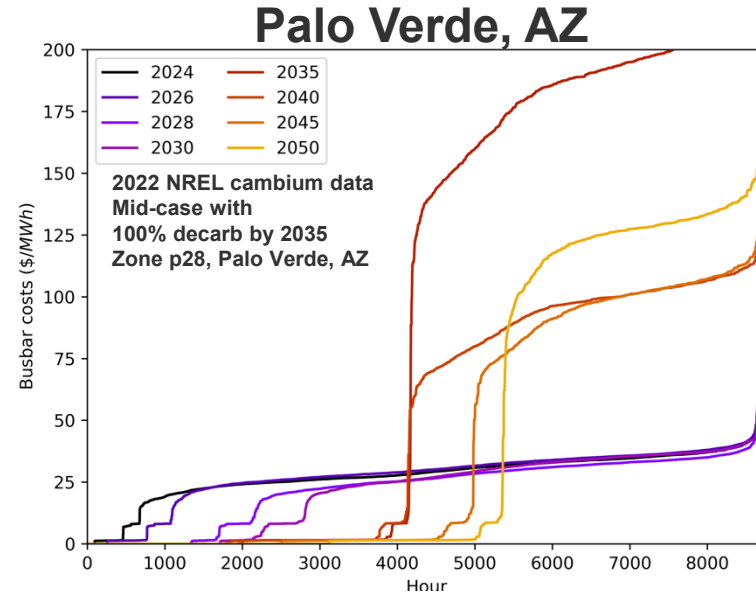
**Amarillo, TX**



# Accomplishment: Analysis of marginal electricity costs over time

- Certain locations could have significant numbers of hours in a year with low to zero marginal cost of energy

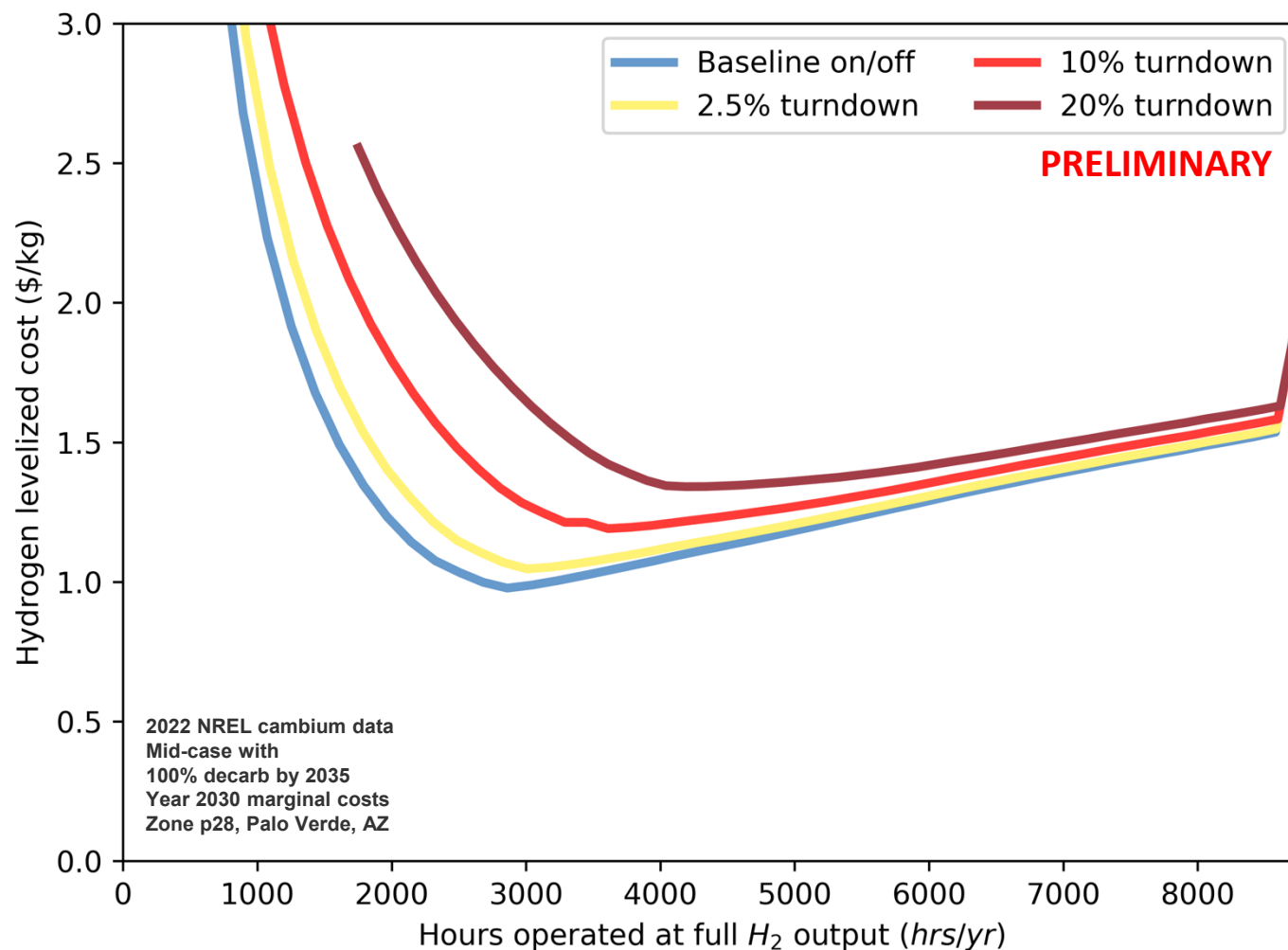
- Distribution of hourly prices in a location directly influence the optimal electrolyzer operating strategy





# Accomplishment: Electrolyzer turndown to idle state to eliminate startup/shutdown cycles

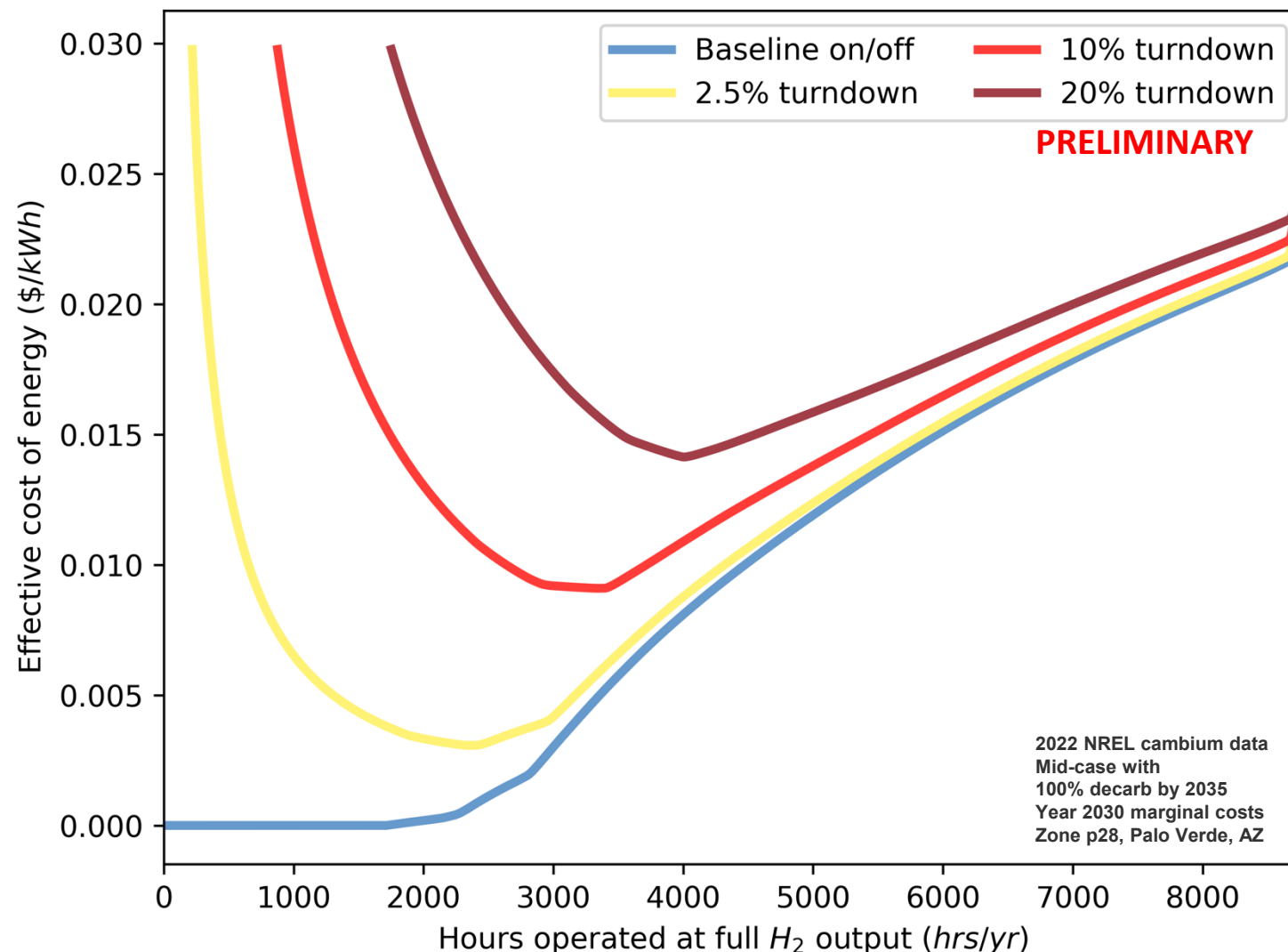
- Distribution of hourly prices in a location directly influence the optimal operating strategy
- Experimental work in H2NEW indicates that startup shutdown cycles degrade the performance of the electrolyzer over time
- Turndown ratios to minimize startup/shutdown cycles impact minimum production costs, and lowest possible turndown ratios are favorable



Badgett A, Saha P, Brauch J, Pivovar B. SUBMITTED: Decarbonization of the electric power sector and implications for low-cost hydrogen production from water electrolysis 2023;Advanced Sustainable Systems.

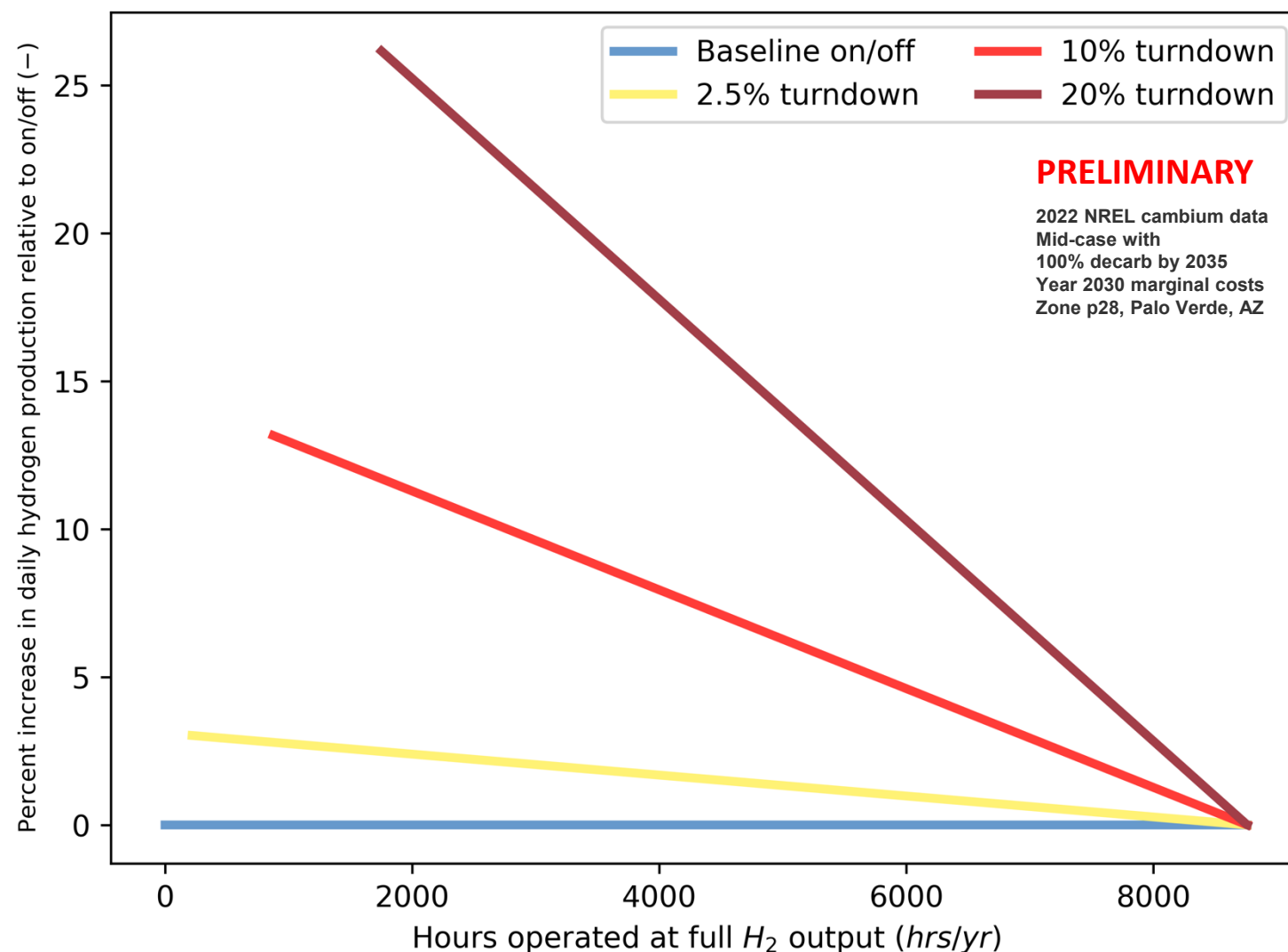
# Accomplishment: Impact of electrolyzer turndown to idle state on electricity cost

- Designating an idle mode and turndown ratio changes the effective cost of electricity for the electrolyzer relative to a full on/off operating mode (shown in blue)
- Electricity costs converge at high operating hours per year but vary significantly at lower operating hours as a function of the turndown ratio

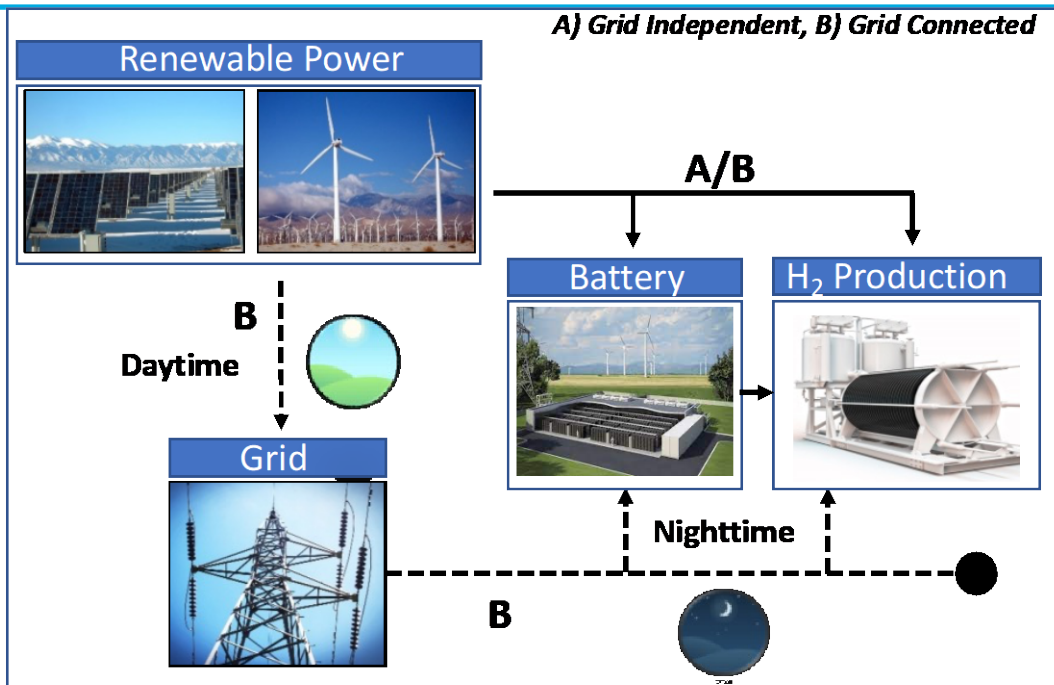


# Accomplishment: Impact of electrolyzer turndown to idle state on average hydrogen production efficiency

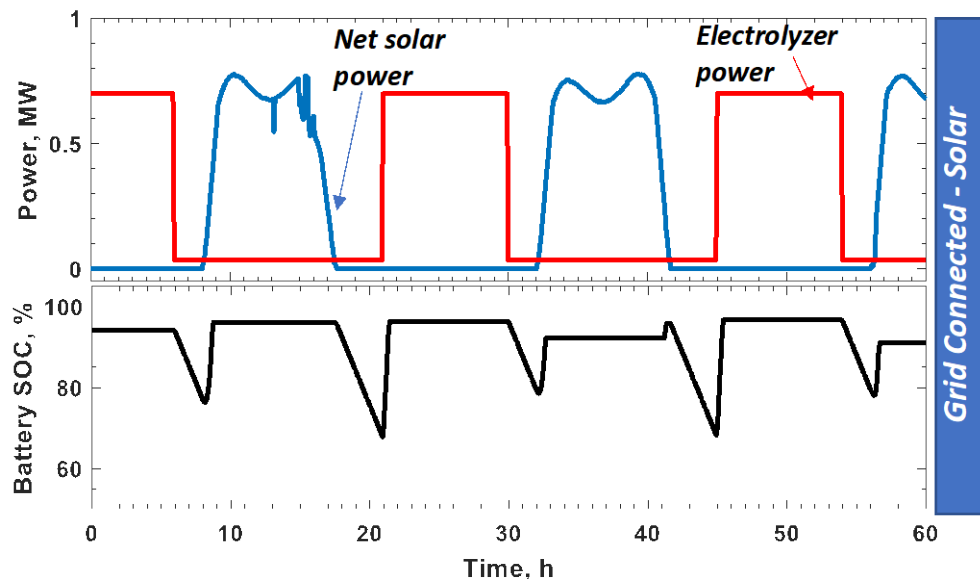
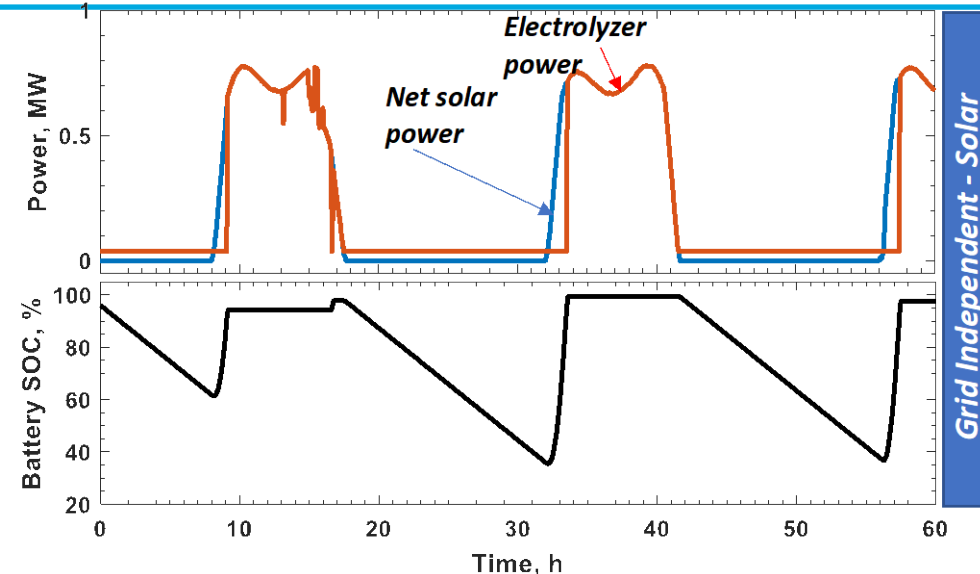
- The electrolyzer produces hydrogen more efficiently on a kWh/kg H<sub>2</sub> basis in standby modes and produces more hydrogen annually since it never shuts fully off
- Increased and slightly more efficient hydrogen production does not offset higher \$/kWh energy costs from standby states on a levelized cost basis (next slide)



# Status/Approach: Grid independent and grid connected electrolysis with battery storage

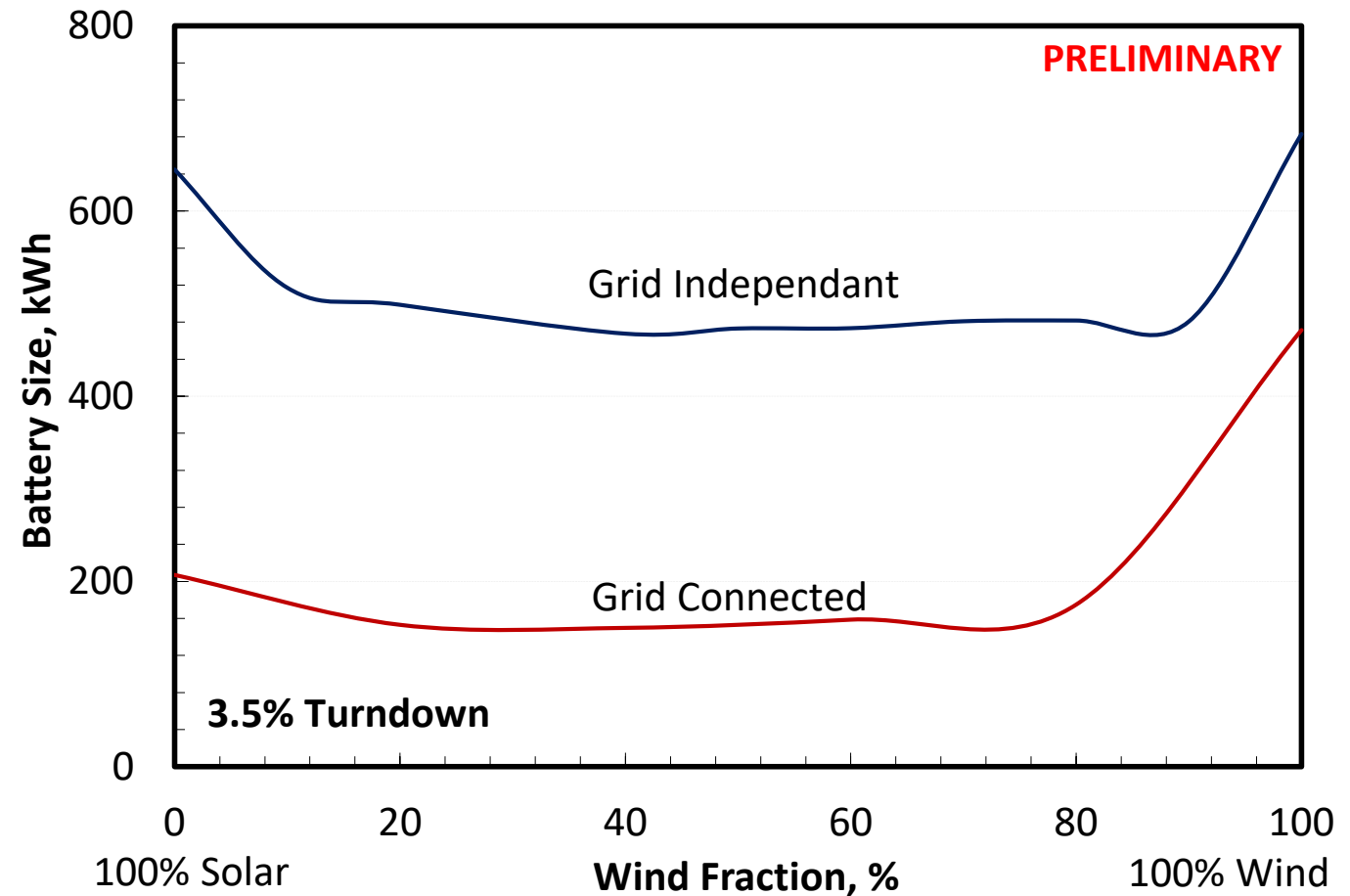


- Electrolyzer**
- Rated power = 1 MW; Minimum power = 0.035-0.1 MW
- Grid Connected**
- Import electricity from grid during night, export during day
  - Zero net kWh to/from grid over the whole year
  - Day time: 6 am to 10 pm
- Grid Independent:**
- Battery supplies all minimum power to electrolyzer. Battery charge is prioritized at power above minimum power to full state of charge (SOC)



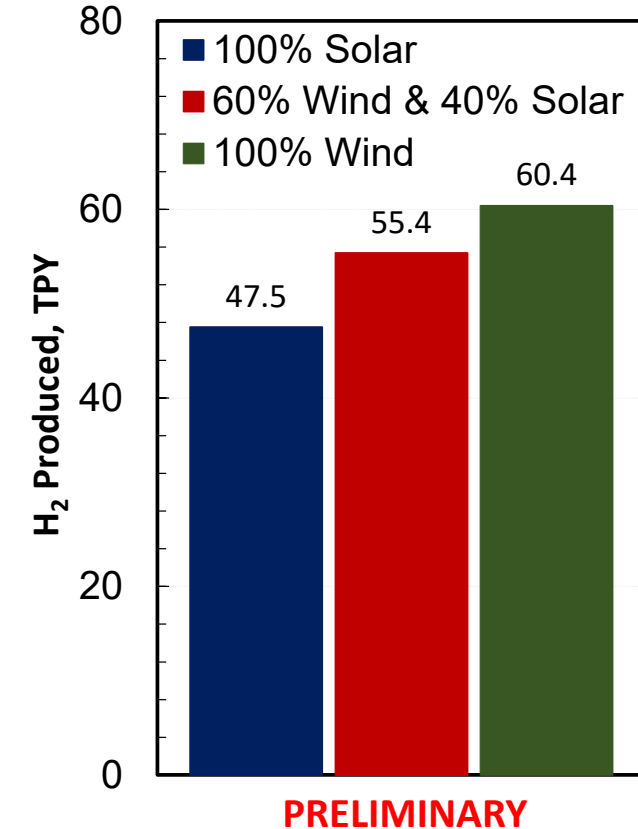
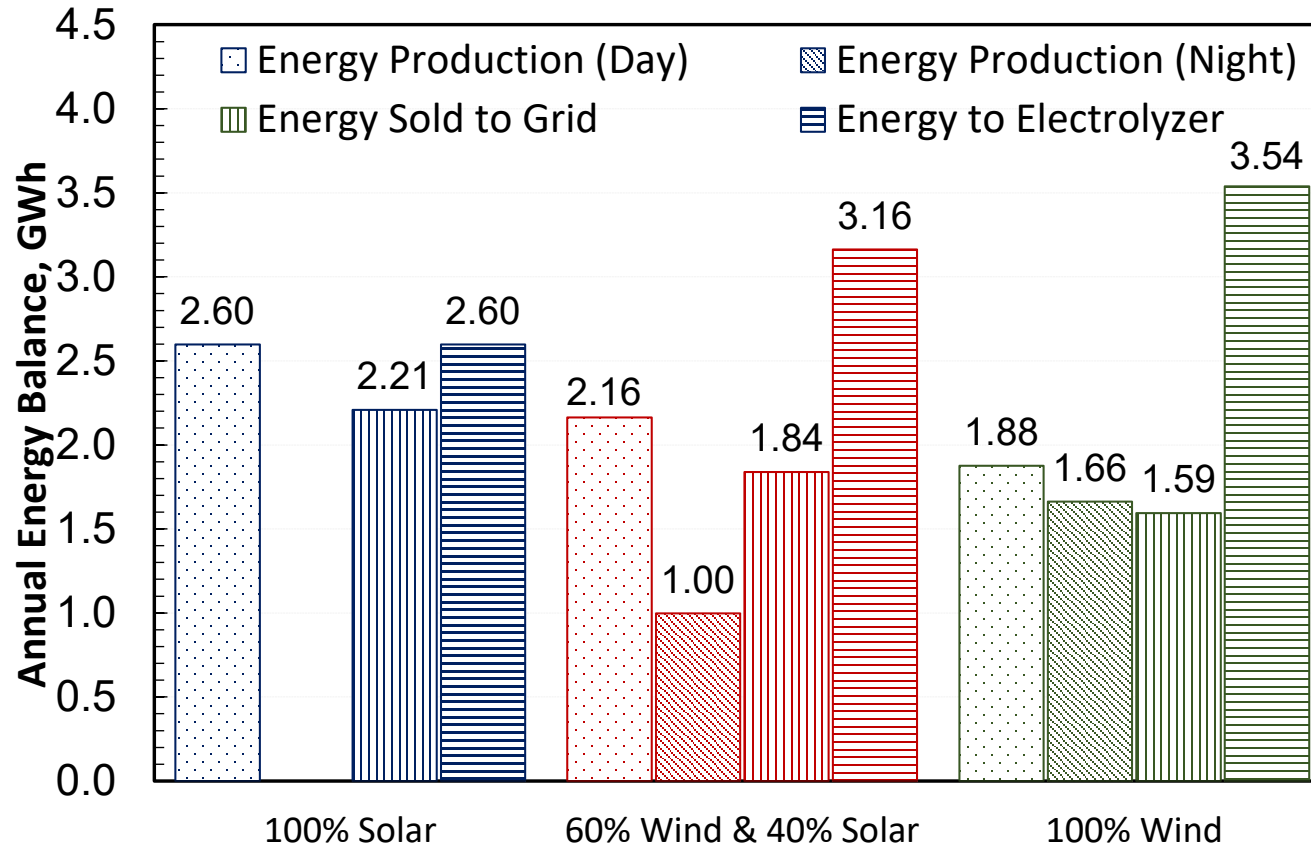
# Accomplishment: Battery sizing for grid independent and grid connected electrolysis

- Grid connection allows the battery to be charged during night and reduces the required battery size
- Because of higher availability during daytime, the required battery size is smaller for solar than wind plants
- Mixing wind and solar can reduce the battery size by 27% below the required size for 100% solar plants.
- Findings from coupling experimental data on electrolyzer degradation can inform stack replacement scheduling and future cost optimization



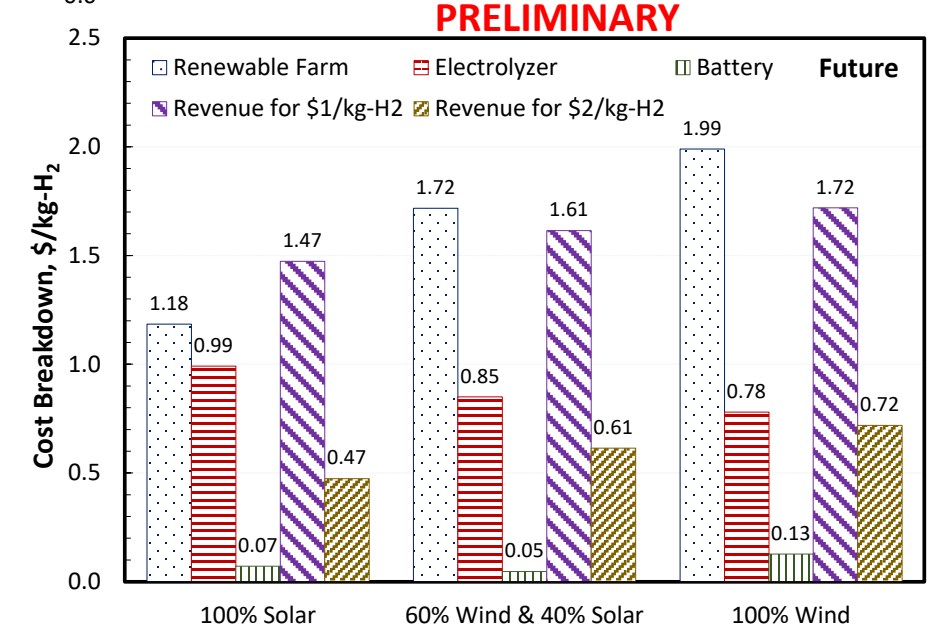
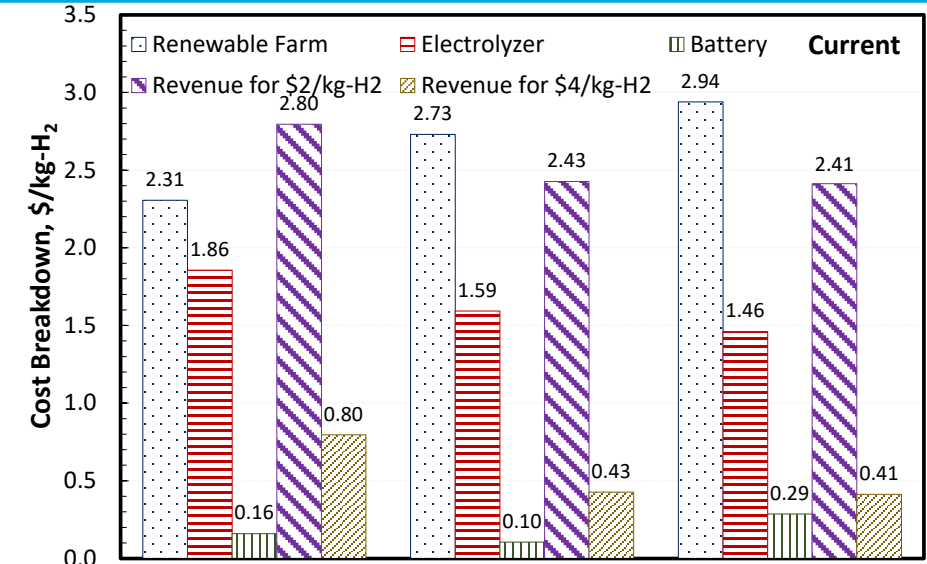
# Accomplishment: Energy balances for grid independent and grid connected electrolysis

- Total energy production: 3.5 GWh (wind) > 3.2 GWh (mix) > 2.6 GWh (solar)
- Energy imported/exported to grid: 2.2 GWh (solar) > 1.8 GWh (mix) > 1.6 GWh (solar)
- Energy to electrolyzer: 3.5 GWh (wind) > 3.2 GWh (mix) > 2.6 GWh (solar)
- H<sub>2</sub> production: 60.4 tpd (wind) > 55.4 tpd (mix) > 47.5 tpd (solar)



# Accomplishment: Levelized cost factors for grid independent and grid connected electrolysis

- Cost Factors:
  - Ordering of levelized (\$/kg-H<sub>2</sub>) cost contributors: Renewable plant > electrolyzer >> battery
  - Levelized cost of renewable plants wind > solar
  - Levelized cost of renewable electricity generation
    - Wind: 5.05 ¢/kWh current, 3.42 ¢/kWh future
    - Solar: 4.25 ¢/kWh current, 2.18 ¢/kWh future
  - H<sub>2</sub> cost without energy credits
    - Wind: 4.41 \$/kg-H<sub>2</sub> current, 2.72 \$/kg-H<sub>2</sub> future
    - Solar: 4.80 \$/kg-H<sub>2</sub> current, 2.47 \$/kg-H<sub>2</sub> future



# Accomplishments: Responses to Previous Year Reviewers' Comments

**This project was not reviewed in the previous year, however reviewer comments on 2021 H2NEW overview presentation (P196) relevant to task 3c are discussed below:**

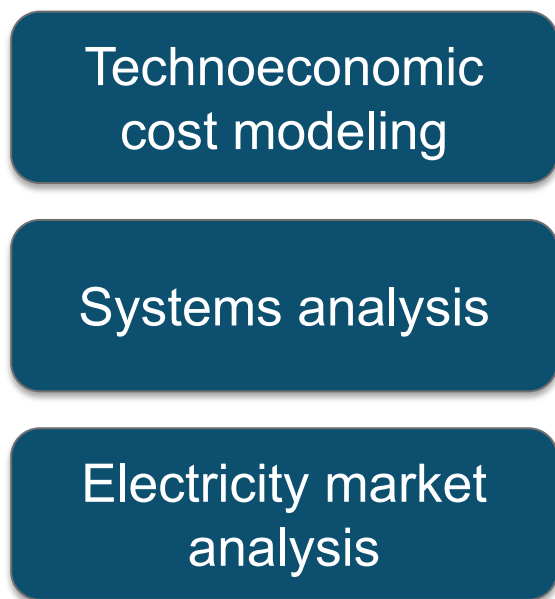
- The LTE waterfall graph showing \$0.86/kg H<sub>2</sub> for the ultimate goal seems to require about \$0.01/kWh electricity. This assumption should be clearly stated, as it may not be realistic as an average price for intermittent electricity.
  - Response: We agree with the reviewer that achieving such low costs for energy likely require low capacity factor operation, dynamic operating strategies, and durable electrolyzers. Collectively considering these factors and their resulting impacts on the economics of hydrogen production is one of the key objectives of H2NEW task 3c.
- Alkaline electrolysis is not addressed in the project, yet there have been substantial technology advances in recent years, and it is likely to capture a large market share in 2030 and beyond.
  - Response: Project workscope in FY23 has been expanded to include liquid alkaline technologies, with future work on this topic planned in outyears.
- There should be even more emphasis on facilitating scale-up of electrolyzer production. The benefits of economies of scale are a huge assumption behind estimates of future low-cost electrolyzers.
  - Response: We agree with the reviewer feedback on the relevance of achieving rapid scale-up of electrolyzer manufacturing, both in terms of achieving cost reductions and in meeting rapidly increasing demand for electrolyzer deployments. Technoeconomic cost modeling in task 3c is explicitly focused on mapping cost trajectories and reduction strategies for various electrolyzer designs, providing a basis for the experimental work ongoing across the consortium.
- It is not clear how the attained information from this project can be used to achieve \$1/kg H<sub>2</sub>.
  - Response: We agree with the reviewer that is important to benchmark progress towards DOE cost targets across activities in the consortium. It is the goal of H2NEW task 3c to provide a \$/kg H<sub>2</sub> cost basis for experimental work, ensuring that these activities target the biggest cost drivers for hydrogen production from electrolysis.



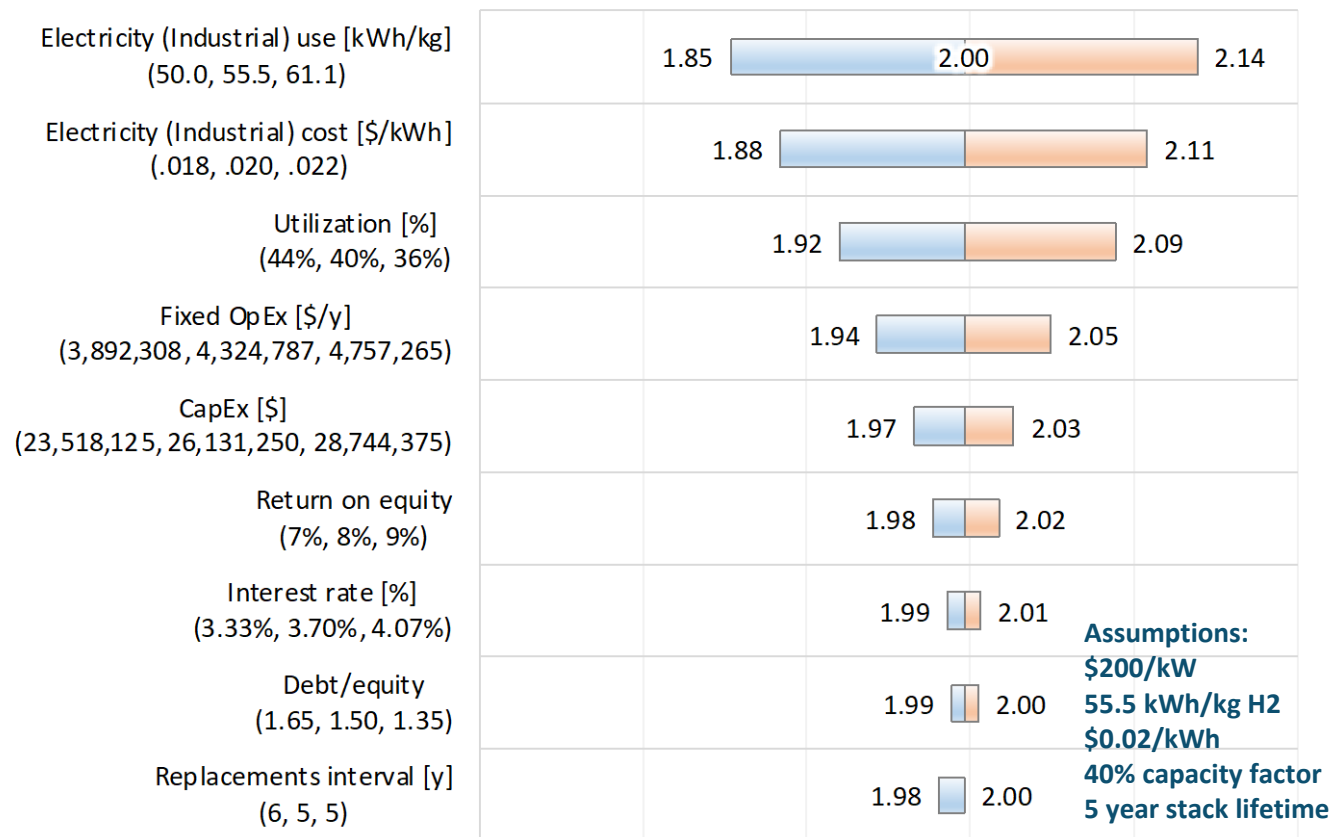
# Summary: How research activities in H2NEW address the biggest cost levers in hydrogen production

- Research in task 3c addresses the top cost drivers of hydrogen production in current and future electrolyzer technologies
- Experimental R&D across the consortium guides inputs and assumptions in analysis tasks, which support benchmarking progress towards DOE cost targets

## H2NEW task 3c activities

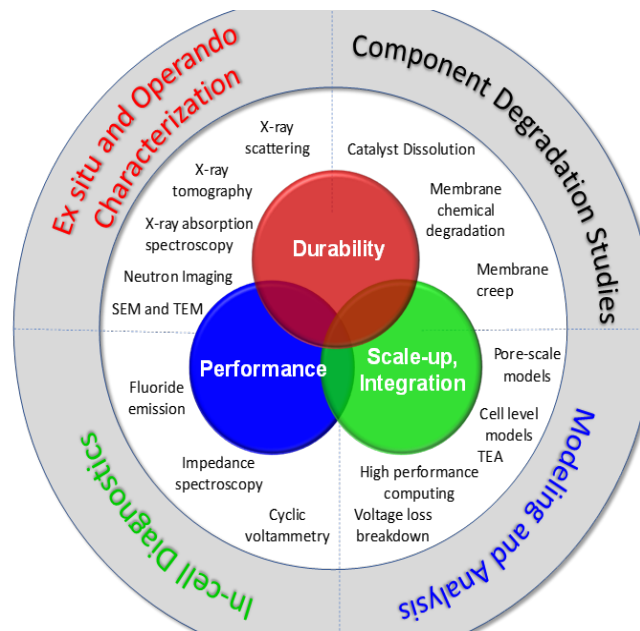


### Possible future scenario – not reflective of current status



- Cross-task collaboration and data exchange is key to ensuring consistency across assumptions
- Frequent collaboration ensures that activities in task 3c are informed by experimental work across the consortium and vice versa

## H2NEW task 1-3 activities



### Key data exchanges and collaboration:

1. Experimental degradation studies
2. Electrolyzer design and materials specifications
3. Manufacturing technologies and optimization
4. Systems analysis performance data

## H2NEW task 3c activities

Technoeconomic cost modeling

Systems analysis

Electricity market analysis

- 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.

- Data gathering efforts to inform analysis of the impact of degradation on technoconomics
- 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

- Ongoing work during FY23
  - Continued analysis of electrolyzers coupled to wholesale power markets and renewable power generation
  - Further work on incorporating degradation, refine curve fits to ensure applicability and build basis for connection to physics-based models
  - Collaborate with experimental researchers to map performance degradation to specific power cycles
  - Development of liquid alkaline analysis capabilities, building basis for comparative modeling of operating strategies, turndown ratios, and degradation rate
- Planned work during outyears
  - Understand iridium thrifting opportunities and tradeoffs between loading and degradation rates between operating strategies
  - Develop estimates for system capital costs when directly connected to renewable generation
  - Determine availability of solar, wind and hybrid plants to provide peak power to grid

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

- 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
- 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
- Collaboration with experimental activities increases the relevance of techno-economic analysis and provides benchmarking for progress towards cost targets
- 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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