Operating strategies for dispatchable PEM electrolyzers that enable low-cost hydrogen production

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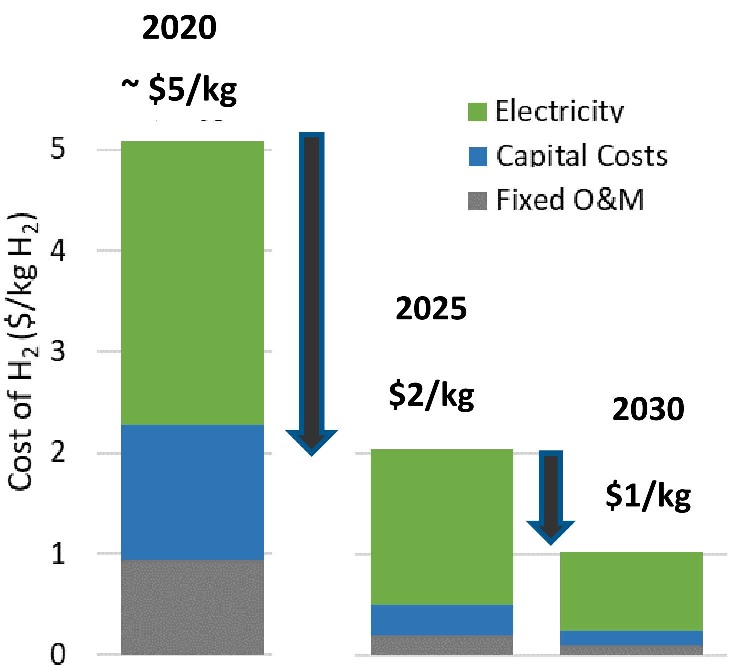
Hydrogen Shot: "1 1 1"
$1 for 1 kg in 1 decade for clean hydrogen

Energy earthshots U.S. Department of Energy | Hydrogen

Launched June 7, 2021
Summit Aug 31-Sept 1, 2021

Example: Cost of Clean H_2 from Electrolysis



Electrolysis:

Reduce electricity cost from >$50/MWh to
- $30/MWh (2025)
- $20/MWh (2030)

- Reduce capital cost >80%
- Reduce operating & maintenance cost >90%

Bipartisan Infrastructure Law – $9.5B H2 Highlights
- $8B for at least 4 regional clean H2 Hubs
- $1B for electrolysis (and related H2) RD&D
- $0.5B for clean H2 technology mfg. & recycling R&D

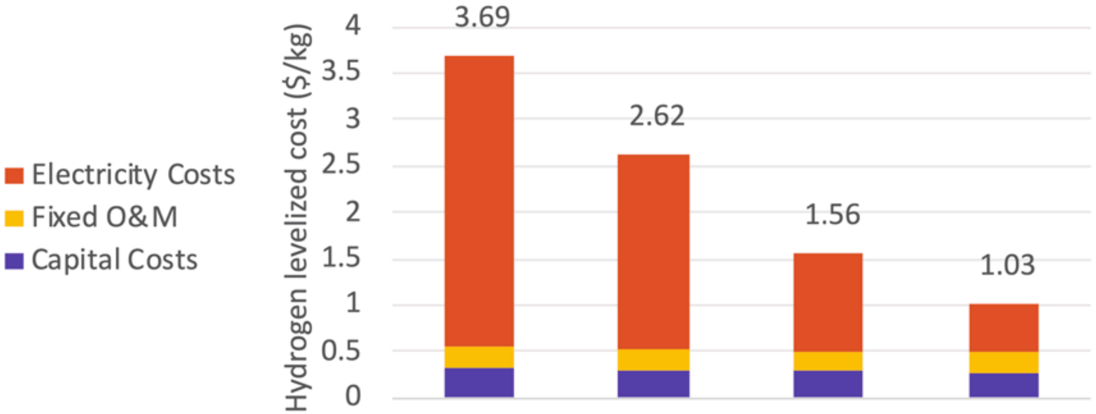
- Aligns with H2 Shot priorities by directing work to reduce cost of clean H2 to $2/kg by 2026
- Requires developing a National H2 Strategy & Roadmap

2020 Baseline: PEM low volume capital cost ~$1,500/kW, electricity at $50/MWh. Need less than $300/kW by 2025, less than $150/kW by 2030 (at scale)

(Adapted from multiple briefing slides from Sunita Satyapal, DOE's HFTO)

For electrolysis at scale, electricity prices are the largest component of the hydrogen production cost

Historically, electricity prices have been fixed in technoeconomic assessments (TEAs)



Electricity price	$0.06/kWh	$0.04/kWh	$0.02/kWh	$0.01/kWh
Capital cost	$400/kW	$400/kW	$400/kW	$400/kW
Capacity factor	97%	97%	97%	97%

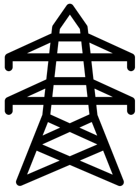
H2A Future Central case. 51.3 kWh/kg system efficiency. Capital costs are total system purchase cost.

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.

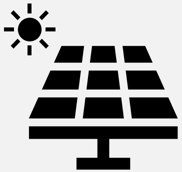
Electrolysis Economics are Driven by Electricity Prices

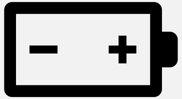
Opportunities to Reduce the Cost of Electricity Supplied to Electrolysis

Integrate with wholesale power markets



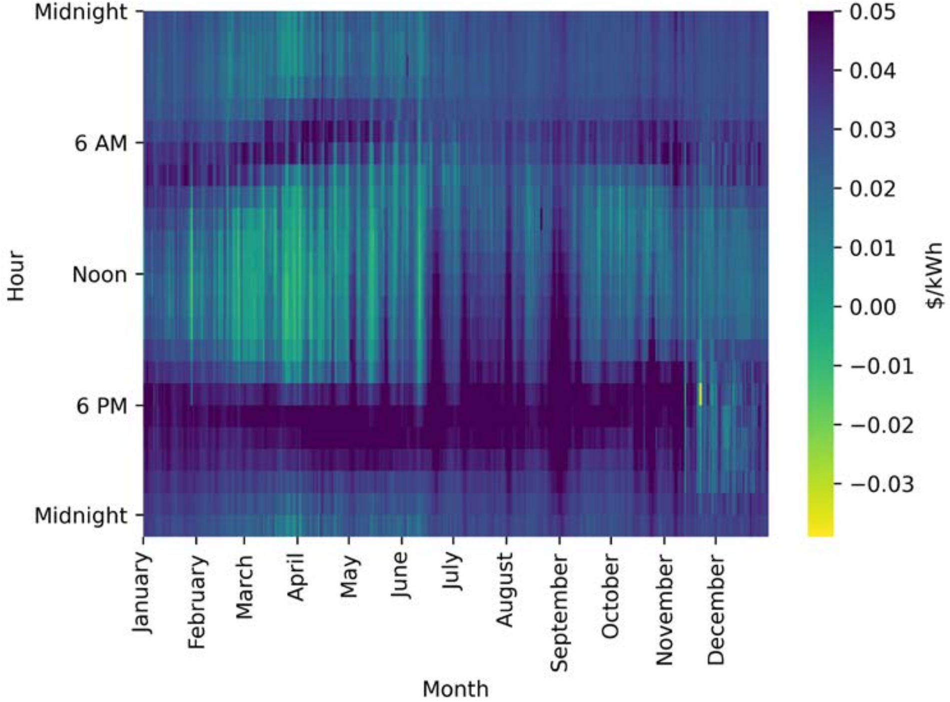
Direct coupling with renewables

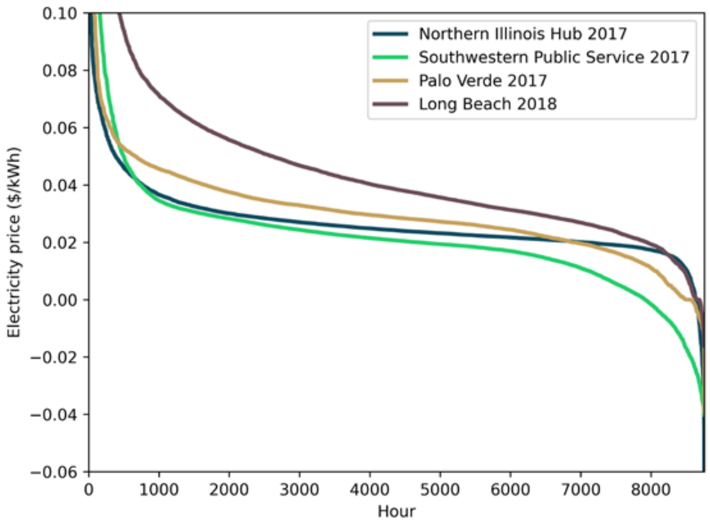


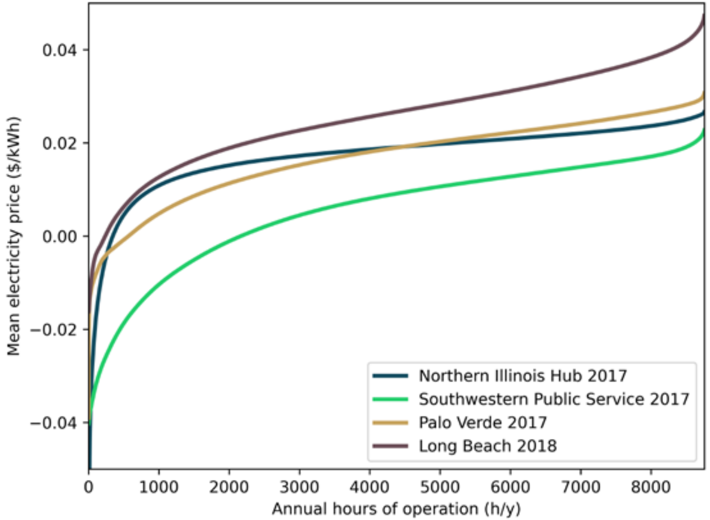


Characteristics of Location Marginal Prices (LMPs)

LMPs for California ISO Palo Verde Node in 2017







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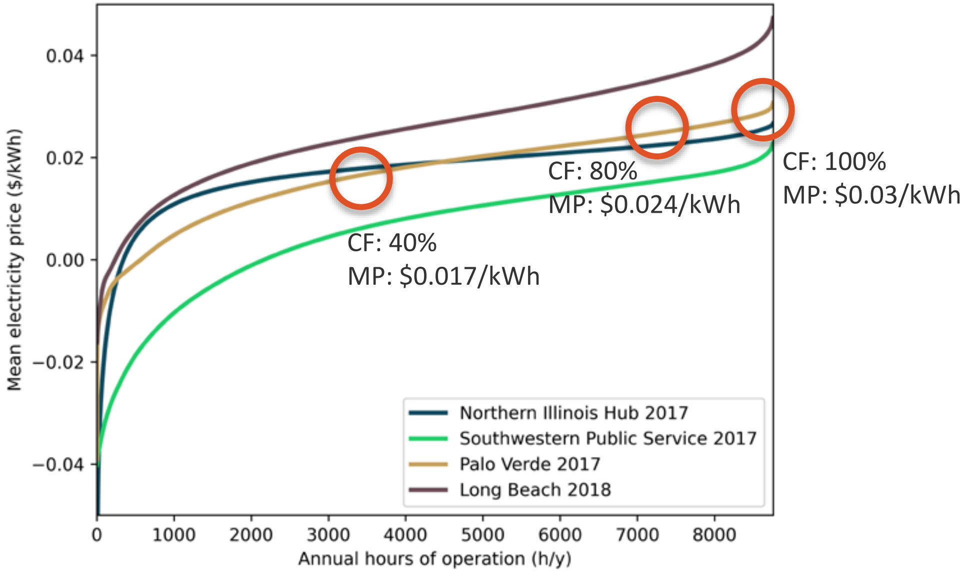
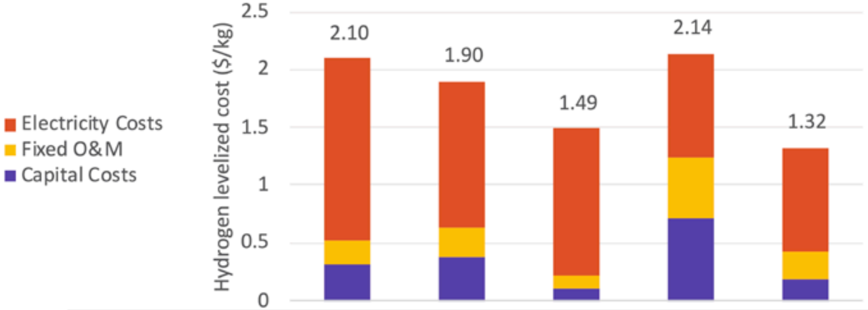
Operating Strategies – Palo Verde

- System cycles on and off to leverage lowest hourly prices
- Intermittent operations combined with access to wholesale LMPs provides opportunities to decrease cost of H2





Electricity price	$0.03/kWh	$0.024/kWh	$0.024/kWh	$0.017/kWh	$0.017/kWh
Capital cost	$400/kW	$400/kW	$100/kW	$400/kW	$100/kW
Capacity factor	100%	80%	80%	40%	40%

H2A Future Central case. 51.3 kWh/kg system efficiency. Capital costs are total system purchase cost. Palo Verde LMPs.

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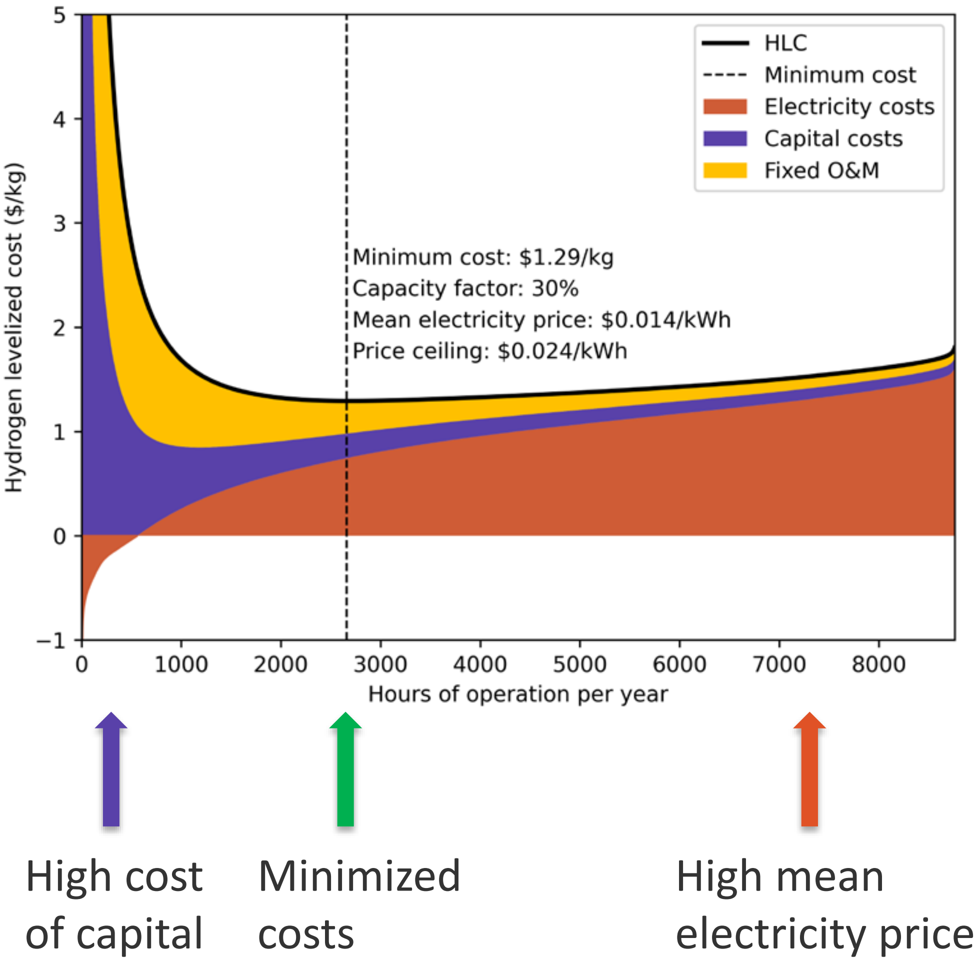
Minimizing Hydrogen Levelized Cost (HLC)

- Achieving minimized H_2 cost depends on the cost of capital and LMPs
- Minimized costs occur at capacity factors around 30%, but depend on LMP characteristics and capital costs



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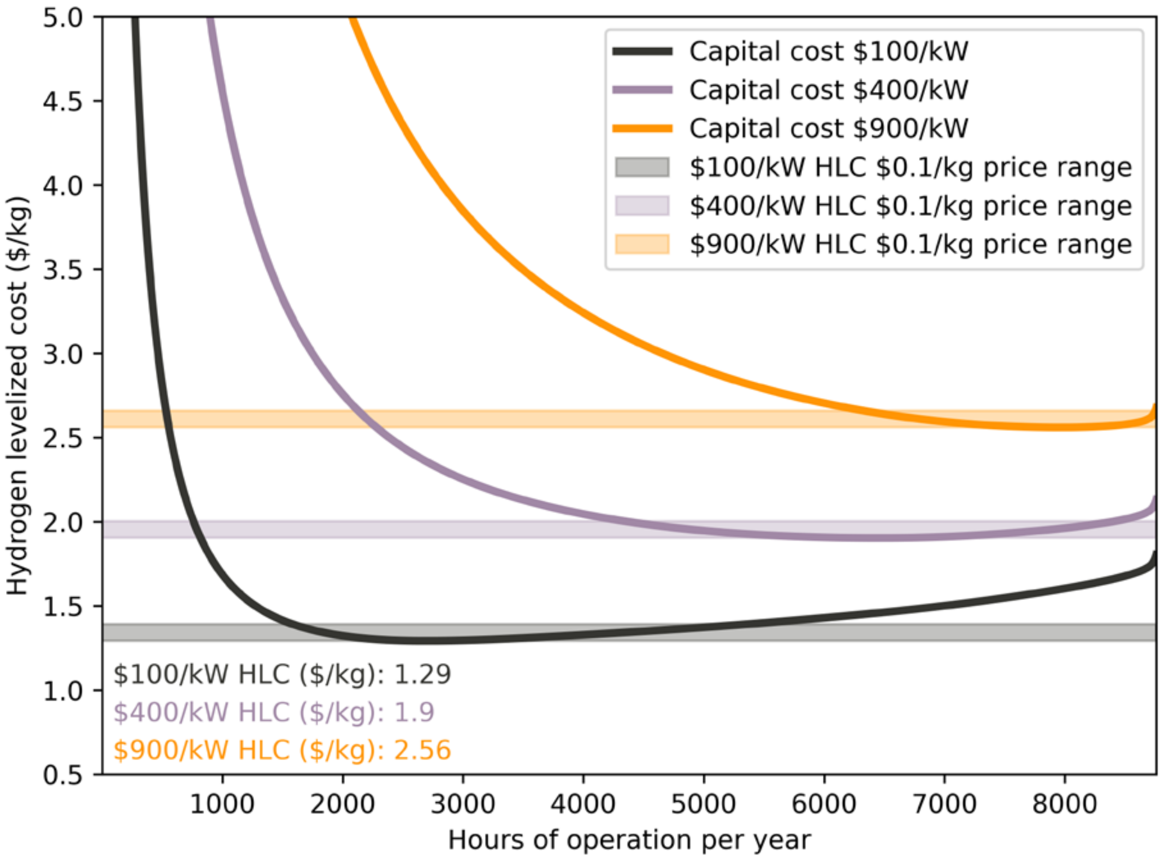
H2A Future Central case. 51.3 kWh/kg system efficiency. $100/kW total system purchase cost. Palo Verde LMPs.

Capital Costs Influence Shape and Minima of HLC Curves

Curves at low capital costs are:

- Lower cost
- Flatter
- Optimum at lower capacity factor



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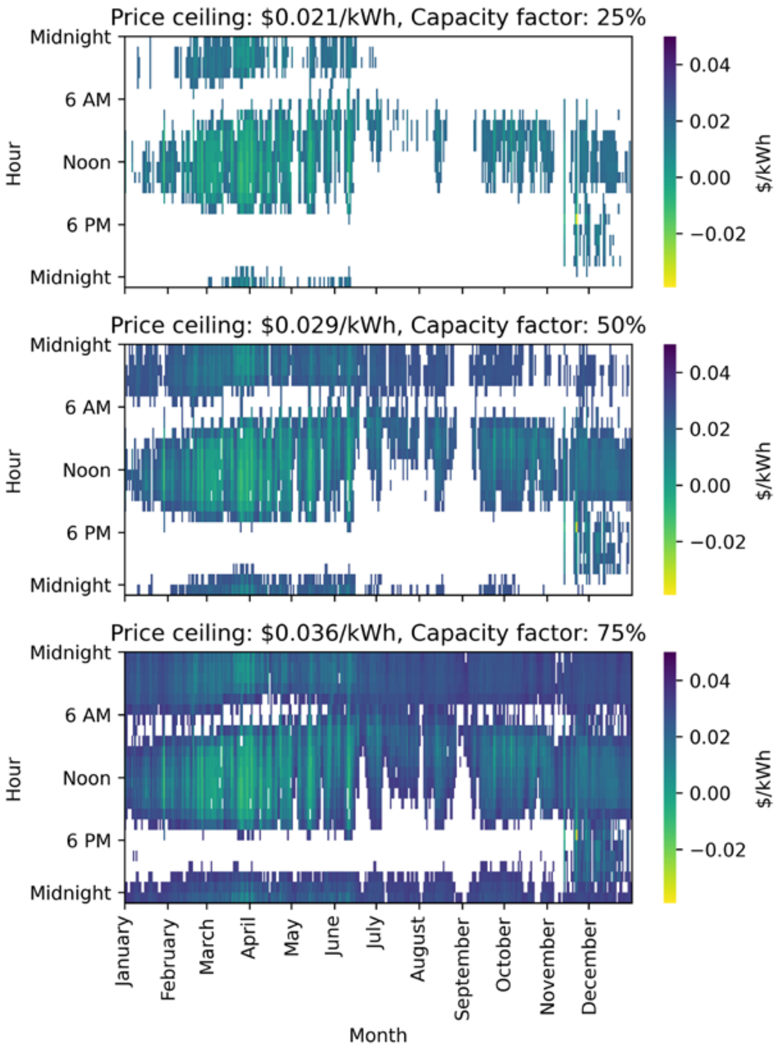
Interacting with an Evolving Grid Requires Frequent Cycling

- Load peaks in the early morning and evening thus those times have highest electricity prices
- PV generation peaks midday and wind peaks in morning/evening
- Electrolysis can capitalize on low LMPs, operating as a dispatchable load and providing grid services
- To do so will require frequent on/off cycling



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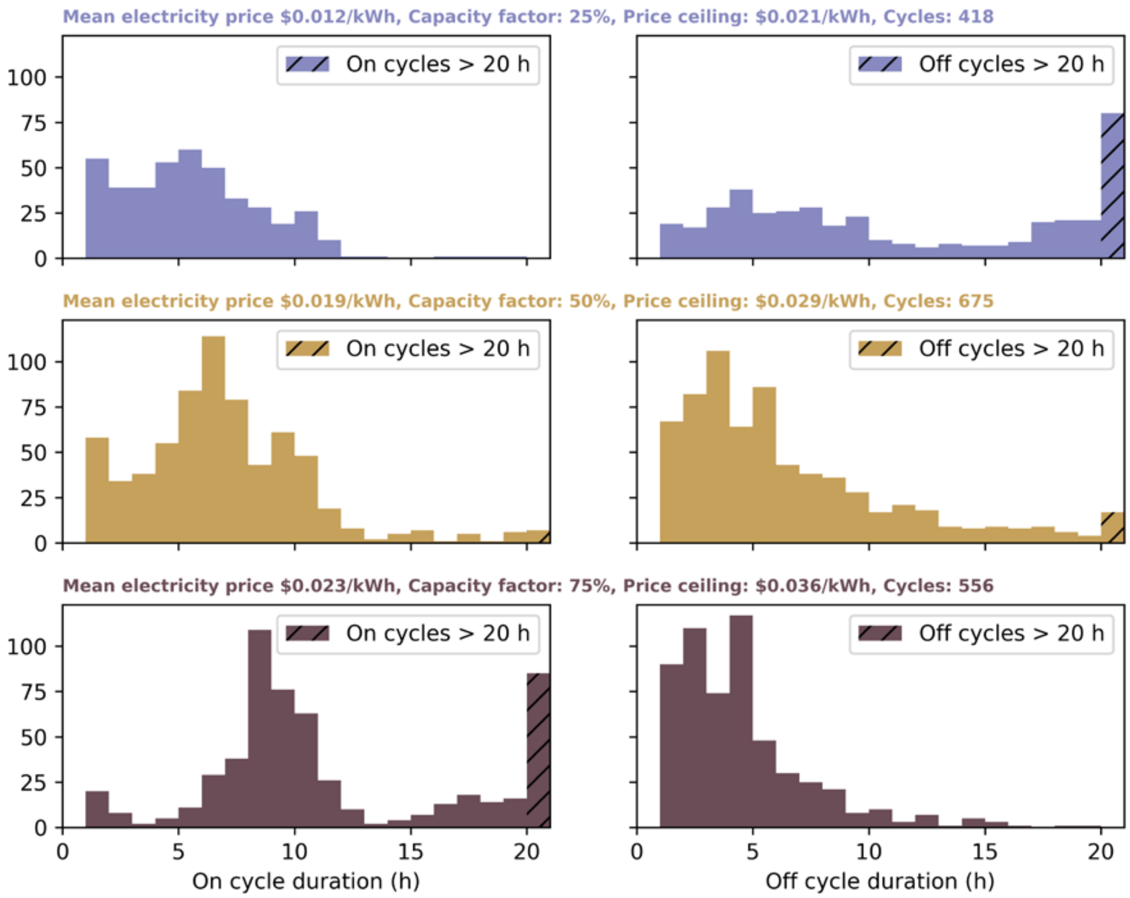
Implications for Electrolyzer Development

Durability implications of cycling are important

Duty cycle requirements and research direction are intermeshed



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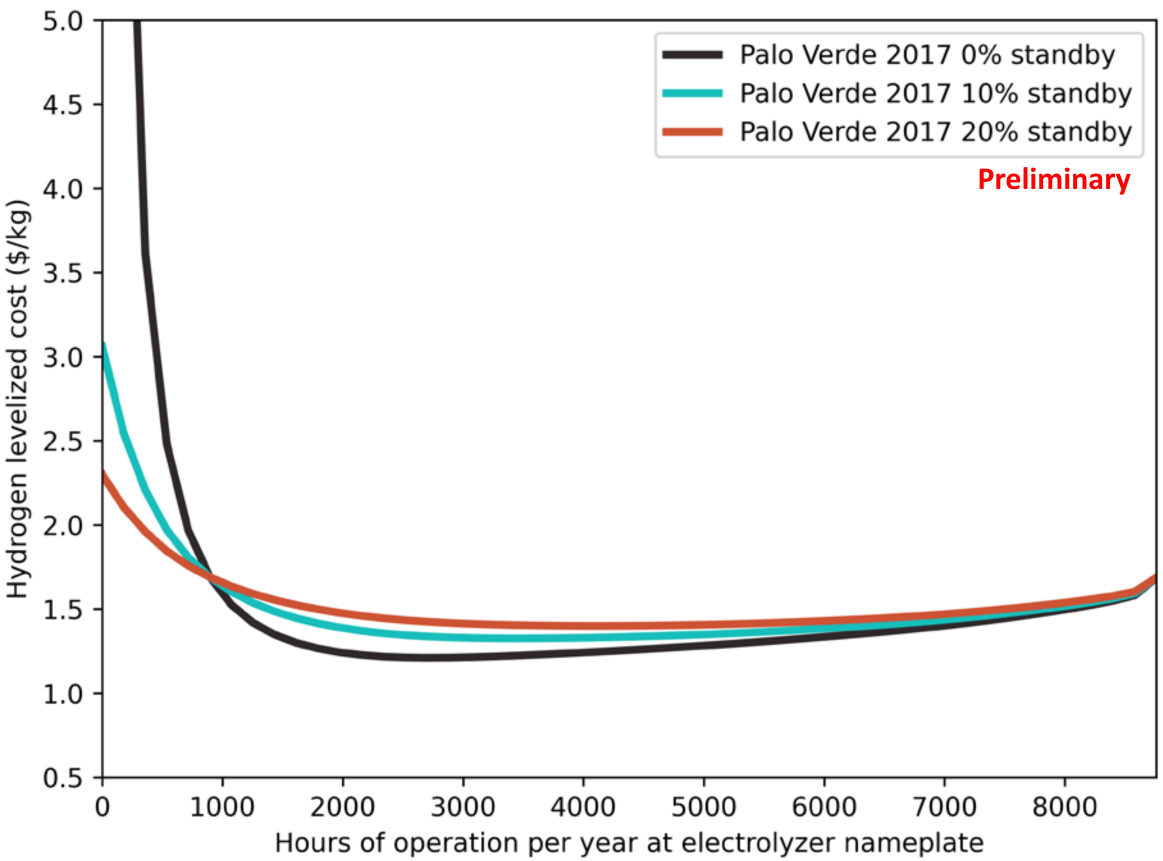
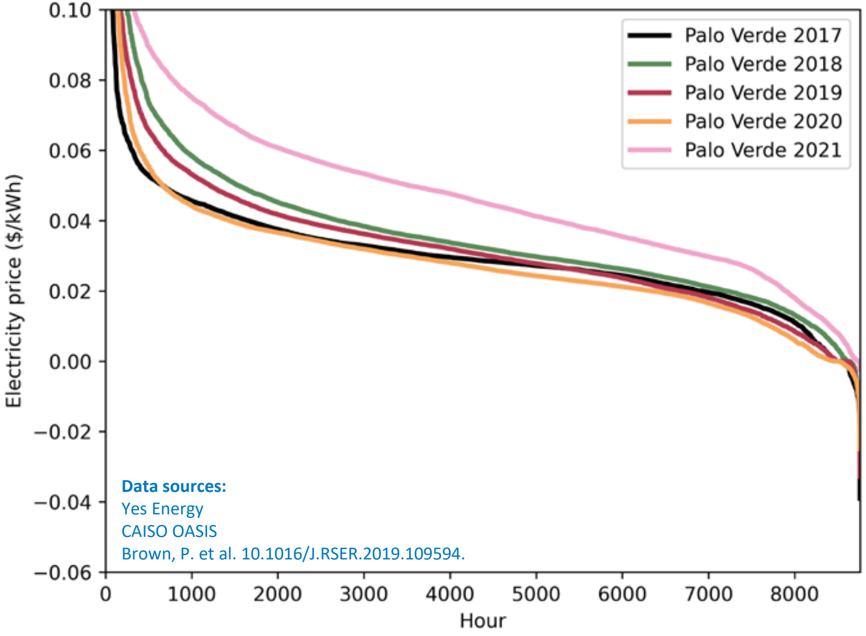
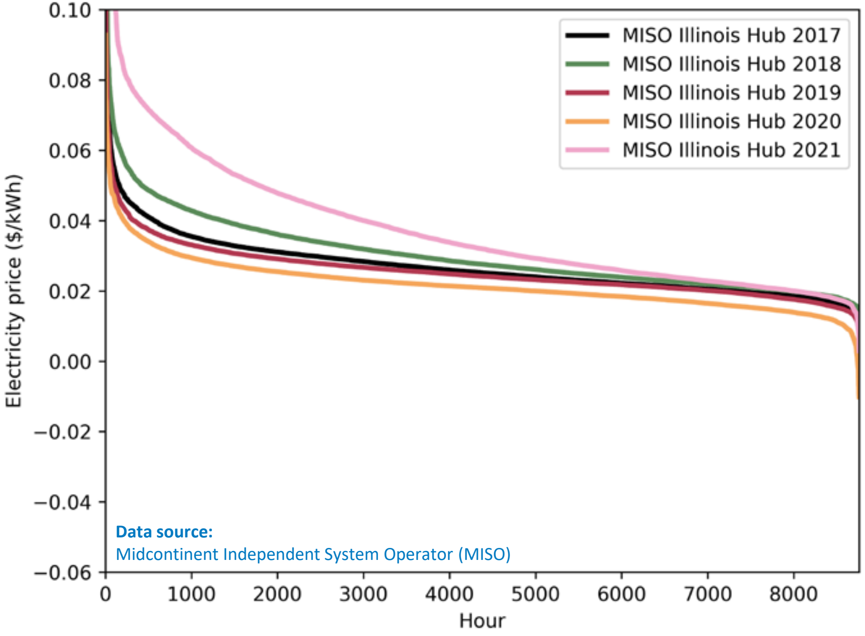
Tradeoffs of Standby Electrolyzer Operation

- Instead of shutting down electrolyzer could ramp down to a standby percentage of nameplate capacity
- Standby mode increases energy costs and HLC but avoids on/off cycling
- HLC minimum for standby mode occurs at a higher capacity factor (about 55%)



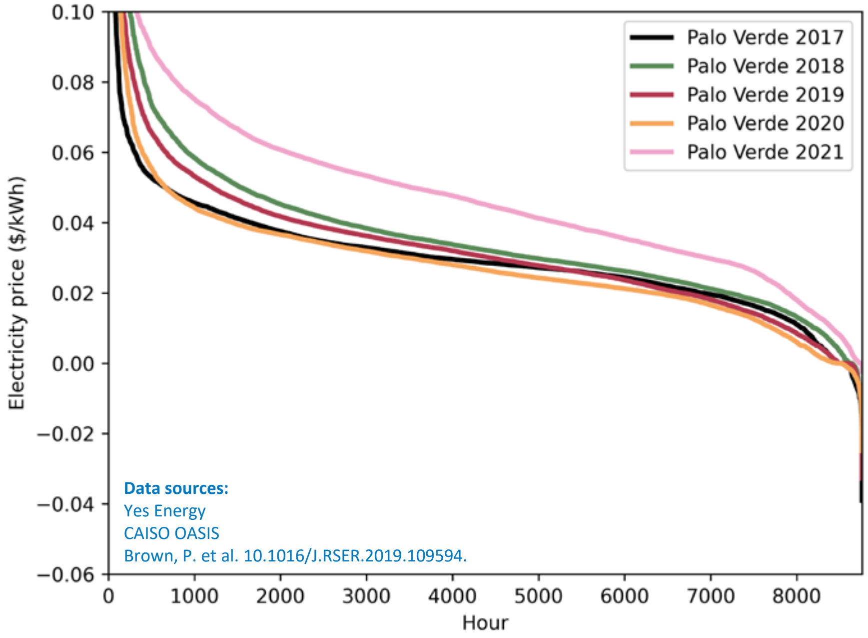
H2A Future Central case. 51.3 kWh/kg system efficiency. Capital costs are $100/kW.
Palo Verde LMPs from:
Brown, P. R. and O'Sullivan, F. M. https://doi.org/10.1016/j.rser.2019.109594

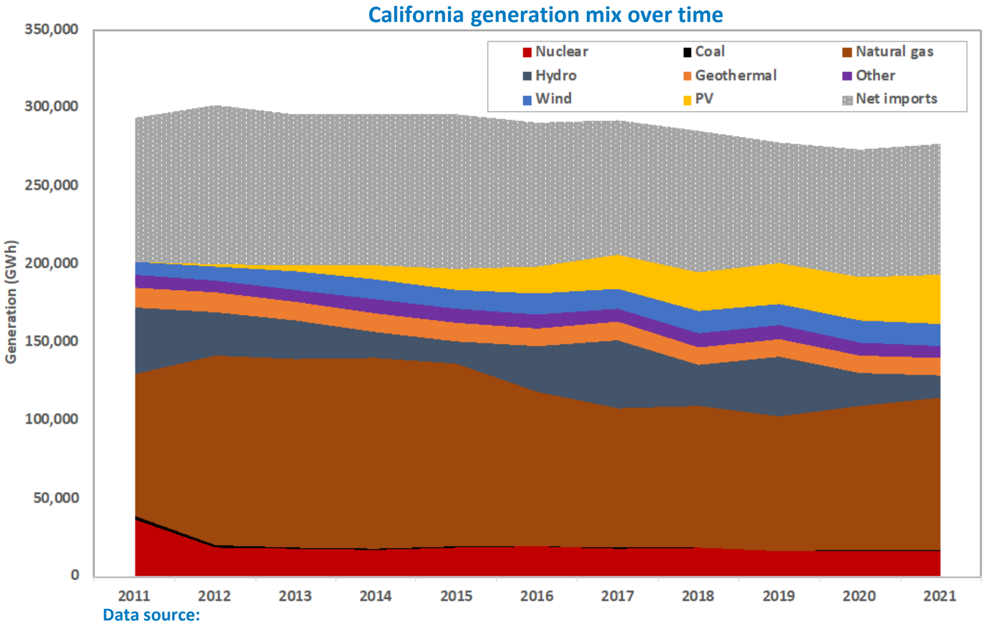




LMPs Vary from Year to Year from Energy Market Drivers

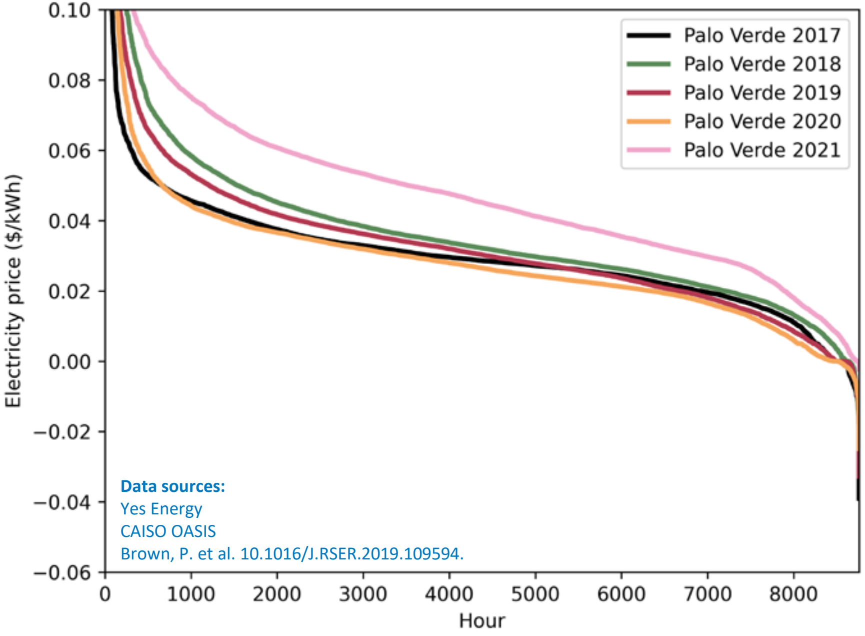
- Demand shifts
- Natural gas prices
- New and retired generation



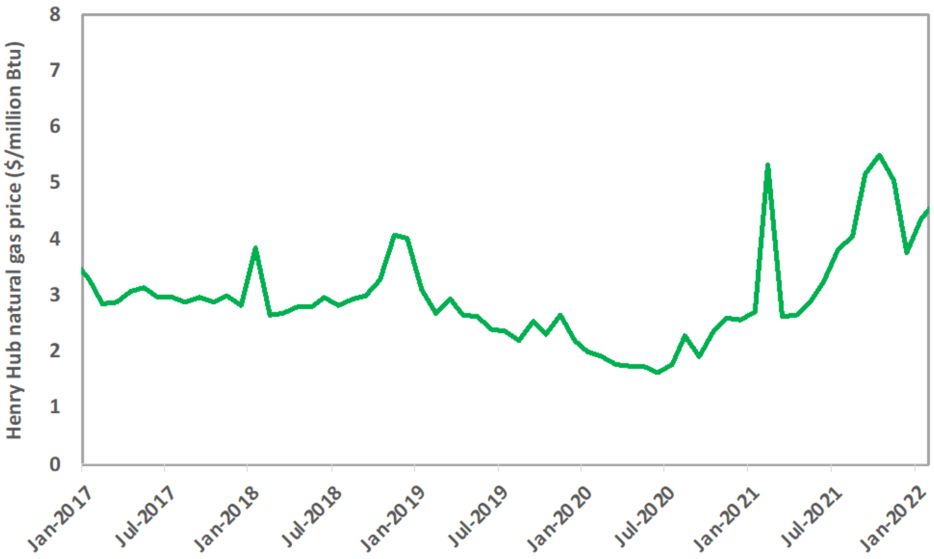


Changes in the generation mix impact the technology "on the margin"

- Increasing variable renewable generation (wind and photovoltaic solar) increases the number of low or negative cost LMPs
- Increasing natural gas generation places it on the margin more often



Data sources:
Yes Energy
CAISO OASIS
Brown, P. et al. 10.1016/J.RSER.2019.109594.



Data source:
U.S. Energy Information Administration

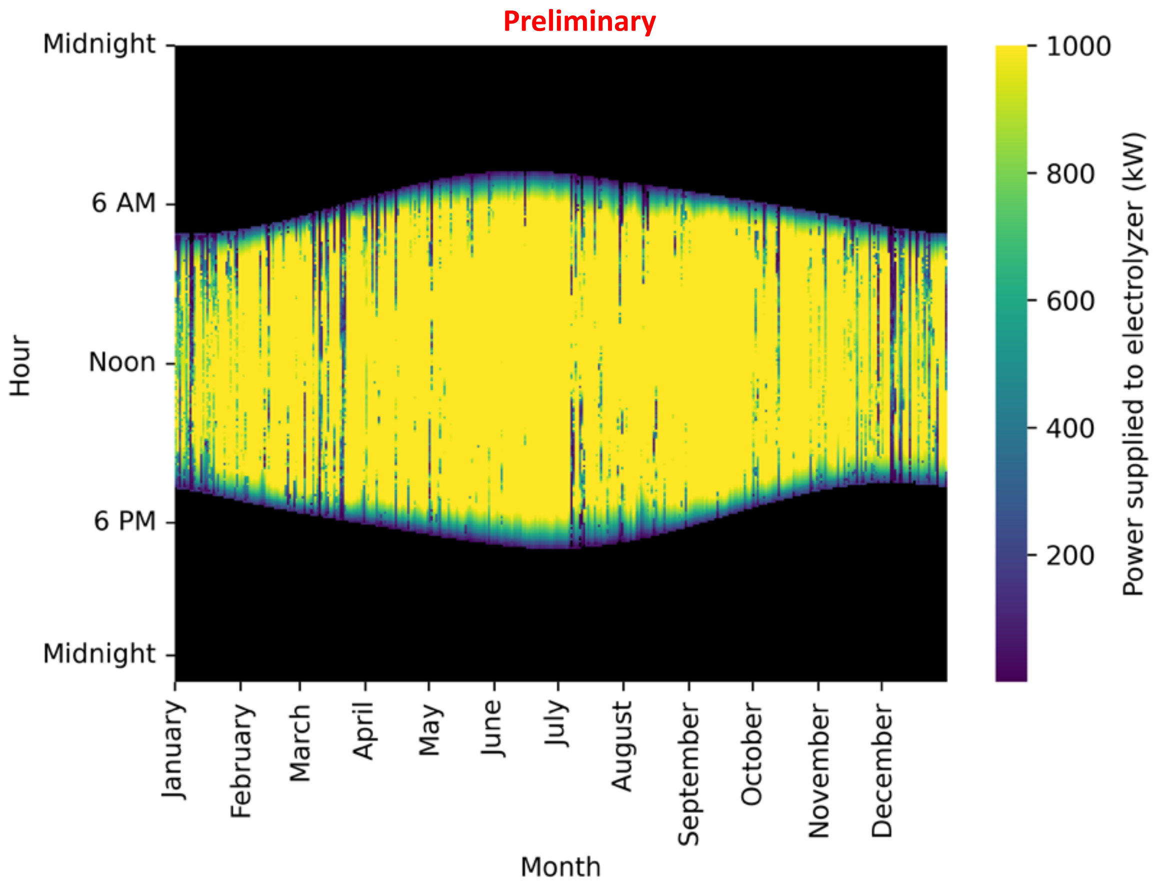
Natural gas prices impact electricity prices when natural gas is "on the margin"

- Natural gas heat rates are 8,000-10,000 Btu/kWh for combustion turbines and 6,000-8,000 Btu/kWh for combined cycle
- At 8,000 Btu/kWh, a $1/MMBtu increase in natural gas price increases the electricity price by $0.008/kWh

Direct Connection with Variable Renewable Generation

Connecting electrolyzers directly to PV or other renewables requires:

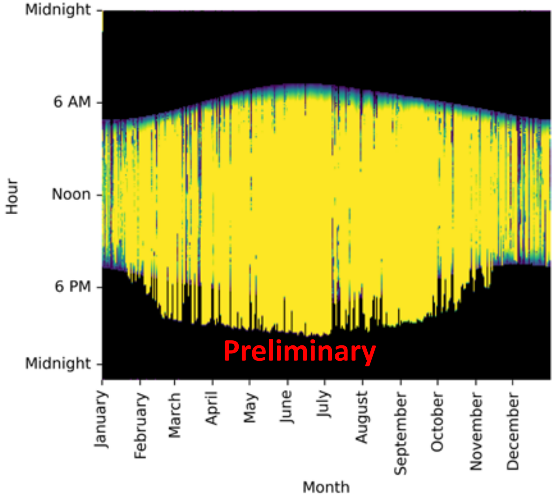
- Electrolyzer to cycle on/off when PV is not generating
- Renewable LCOEs low enough to enable electrolyzer operation at low-capacity factors



PV/electrolyzer oversize ratio: 2
Location: Dagget, CA
PV output simulated with NREL SAM model

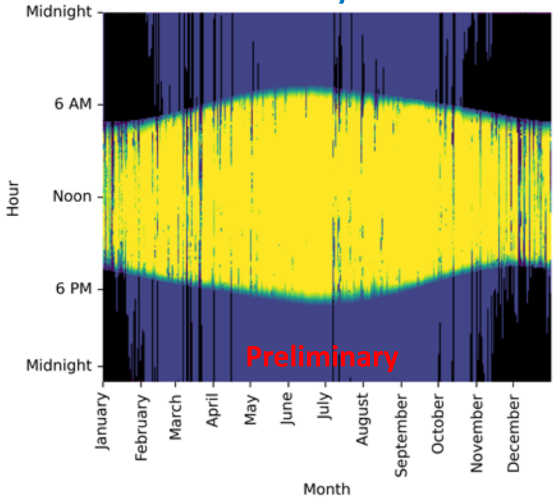
Influence of Batteries and Renewable Sizing

100% dispatch:
PV oversize ratio=2
PEM/battery ratio=1
4hr battery



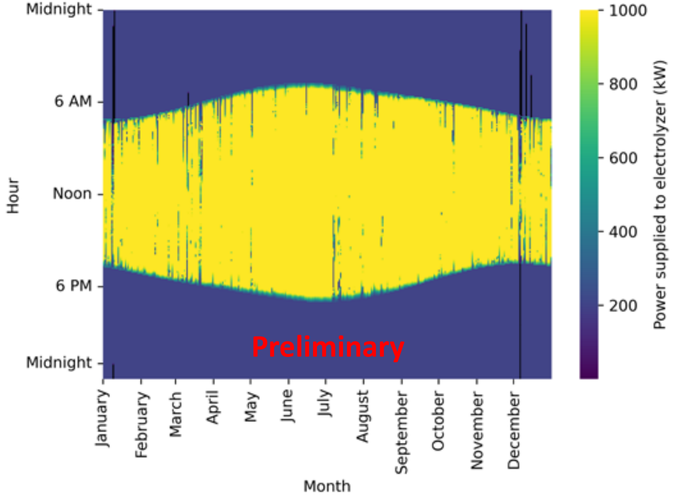
49% capacity factor

20% dispatch:
PV oversize ratio=2
PEM/battery ratio=1
4hr battery



51% capacity factor

20% dispatch:
PV oversize ratio=4
PEM/battery ratio=1
8hr battery

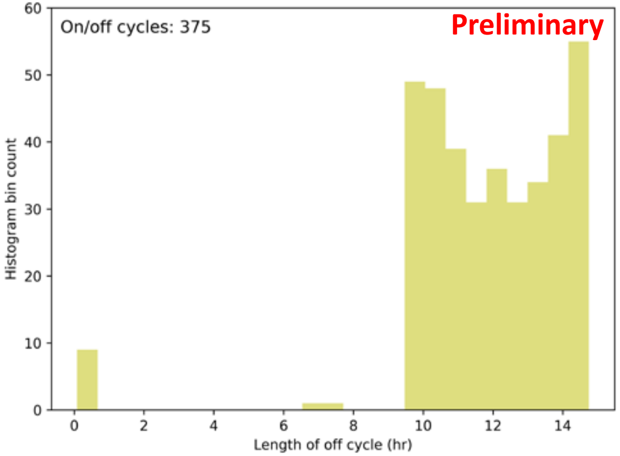


57% capacity factor

- Battery dispatch algorithm can significantly impact electrolyzer operation and reduce on/off cycles
- Oversizing generation relative to electrolyzer improves duty cycles but can result in high curtailment

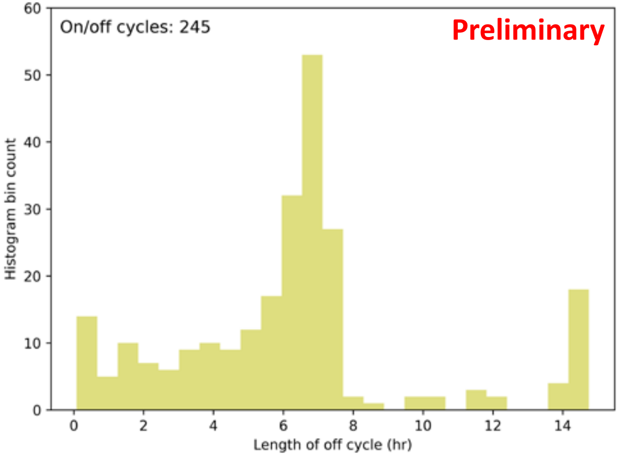
Influence of Batteries and Renewable Sizing

PV oversize ratio: 2
No battery



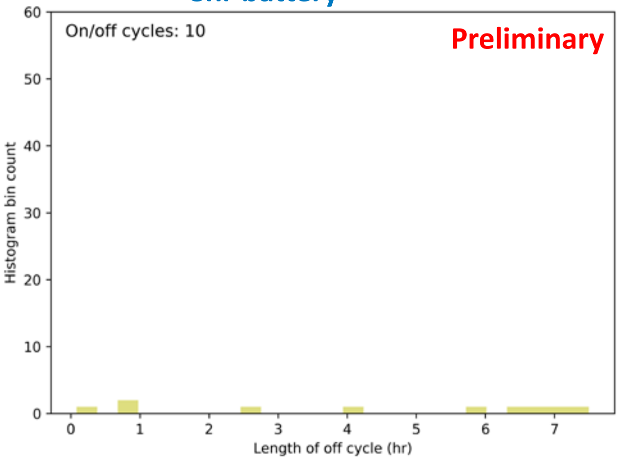
43% capacity factor

20% dispatch with:
PV oversize ratio: 2
4hr battery



51% capacity factor

20% dispatch with:
PV oversize ratio: 4
8hr battery

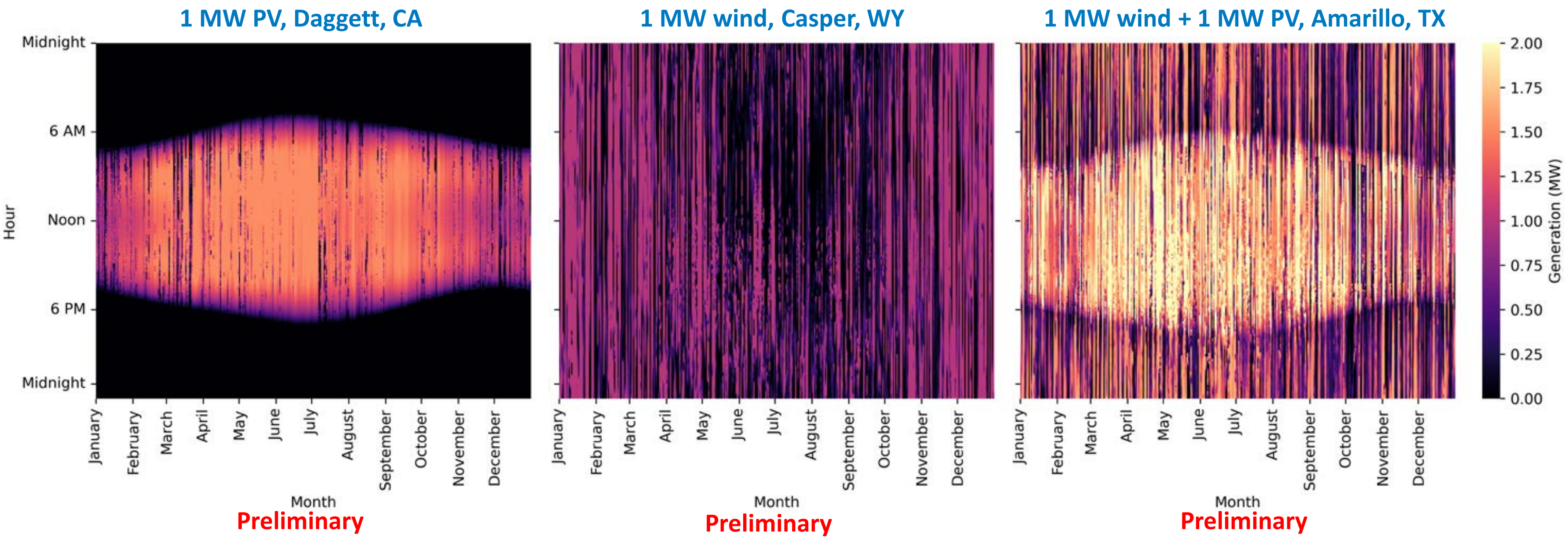


57% capacity factor

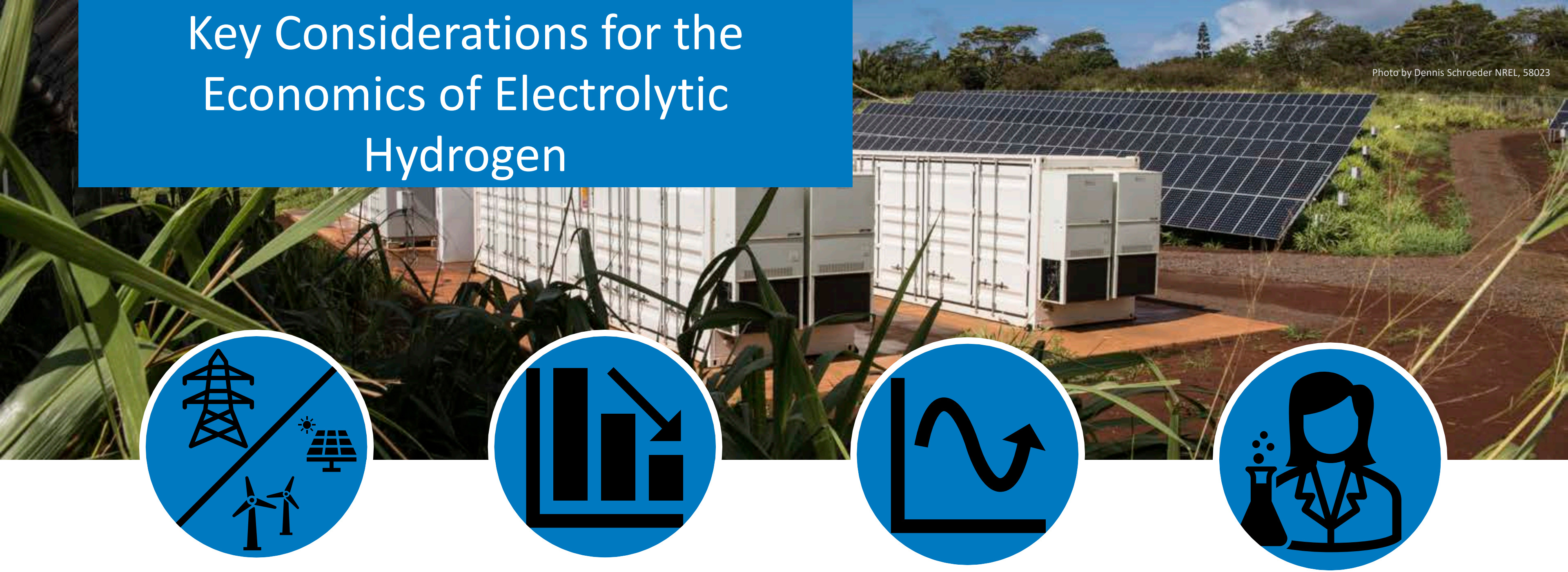
- Batteries can reduce electrolyzer cycling; potentially reducing electrolyzer degradation
- Storing otherwise curtailed energy in batteries could also reduce the average duration of off cycles
- Economic optimization would involve tradeoff between battery cost, increased electrolyzer capacity factor, and degradation resulting from on/off cycling

Hybridized wind and PV

- Hybridizing wind and solar can complement the grid and electrolyzer by reducing on/off cycling and complementing PV diurnal cycles
- Optimizing hybridized systems requires consideration of location, PV/wind nameplate capacity, grid interactions, and electrolyzer duty cycles



Key Considerations for the Economics of Electrolytic Hydrogen



Dispatchable operation enables lower energy costs

As electrolyzer capital costs decrease, dispatchable operation becomes more economic

Impacts of operating strategy on durability are key considerations

Reducing capital cost and maintaining durability are key R&D focuses

Thank You!

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