DOCKETED	
Docket Number:	17-HYD-01
Project Title:	Renewable Hydrogen Transportation Fuel Production
TN #:	227515
Document Title:	Presentation - UCI-APEP Webinar 2 CA Renewable Hydrogen Production Roadmap Interim Findings Implications 4-4-19
Description:	Recent research suggests California will need 5,500 - 7,400 kg/day of retail renewable hydrogen for vehicles in the near term. The Energy Commission Alternative and Renewable Fuel and Vehicle Technology Program (ARFVTP) supported a contract to explore the local renewable hydrogen needs of the various California regions for renewable retail fueling, a "Renewable Hydrogen Production Plant Deployment Roadmap". UCI is conducting this research study gathering California commercial hydrogen fueling data to support a mapping model with several scenarios that will produce optimized 5-year forecasts to 2050. This workshop allows the public to provide input on preliminary, non-optimized results for 5 and 10-year projections, including a hydrogen demand forecast, organic feedstock supply, feedstock cost, electricity cost for electrolyzers, environmental credit scenarios, capital investment requirements, hydrogen pump price scenarios, and siting scenarios for each production technology.
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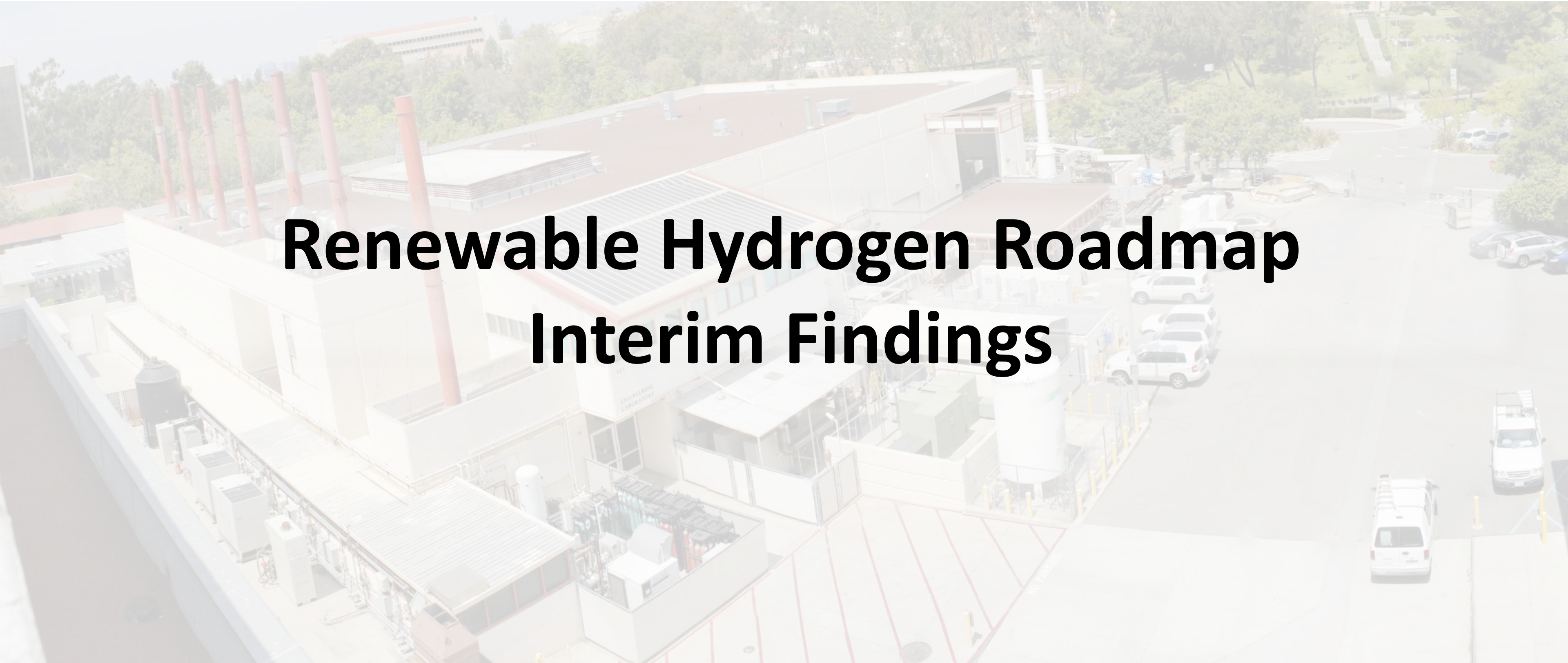
Organization:	University of California Irvine/Advanced Power & Energy Program
Submitter Role:	Public Agency
Submission Date:	4/5/2019 3:43:11 PM
Docketed Date:	4/5/2019



Renewable Hydrogen Roadmap
Interim Findings

ADVANCED POWER
& ENERGY PROGRAM
UNIVERSITY of CALIFORNIA · IRVINE

April 4, 2019

Agenda – Renewable Hydrogen Production Roadmap Update

1:00 PM	Welcome and Diversity Survey	Akasha Kaur Khalsa
	Introductions	Akasha Kaur Khalsa
1:05 PM	Agenda, Acknowledgments and Context	Dr. Scott Samuelsen
1:10 PM	***Overview and Summary***	Dr. Jeff Reed

- Renewable Hydrogen Production Pathways
- Renewable Hydrogen Production Roadmap (Roadmap)
- Interim Findings and Conclusions

1:15 PM	***Renewable Hydrogen Demand and Supply Analysis***	Dr. Jeff Reed / Dr. Brendan Shaffer

- Renewable Hydrogen Demand Scenarios
- Renewable Hydrogen Feedstock and Facility Siting Analysis
- Renewable Hydrogen Delivered Cost Analysis
- Production Build-out Requirements to Meet Demand

1:55 PM	***Getting to a Self-Sustaining Renewable Hydrogen Sector***	Dr. Jeff Reed

- Role of Mandates, Incentives and Credits
- Hydrogen Pump Price Scenarios
- Preliminary Program and Policy Implications

Acknowledgements

FUNDING PROVIDED BY THE
CALIFORNIA ENERGY COMMISSION

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- **Thanks to the Energy Commission Clean Transportation Program for sponsoring the Renewable Hydrogen Roadmap**
- **Thanks to the more than 40 industry and agency stakeholders that have provided input to the effort**

Context and Need for a Renewable Hydrogen Roadmap

- **Extensive analysis has been performed on the optimal build-out of the hydrogen refueling network – but not for the production end**

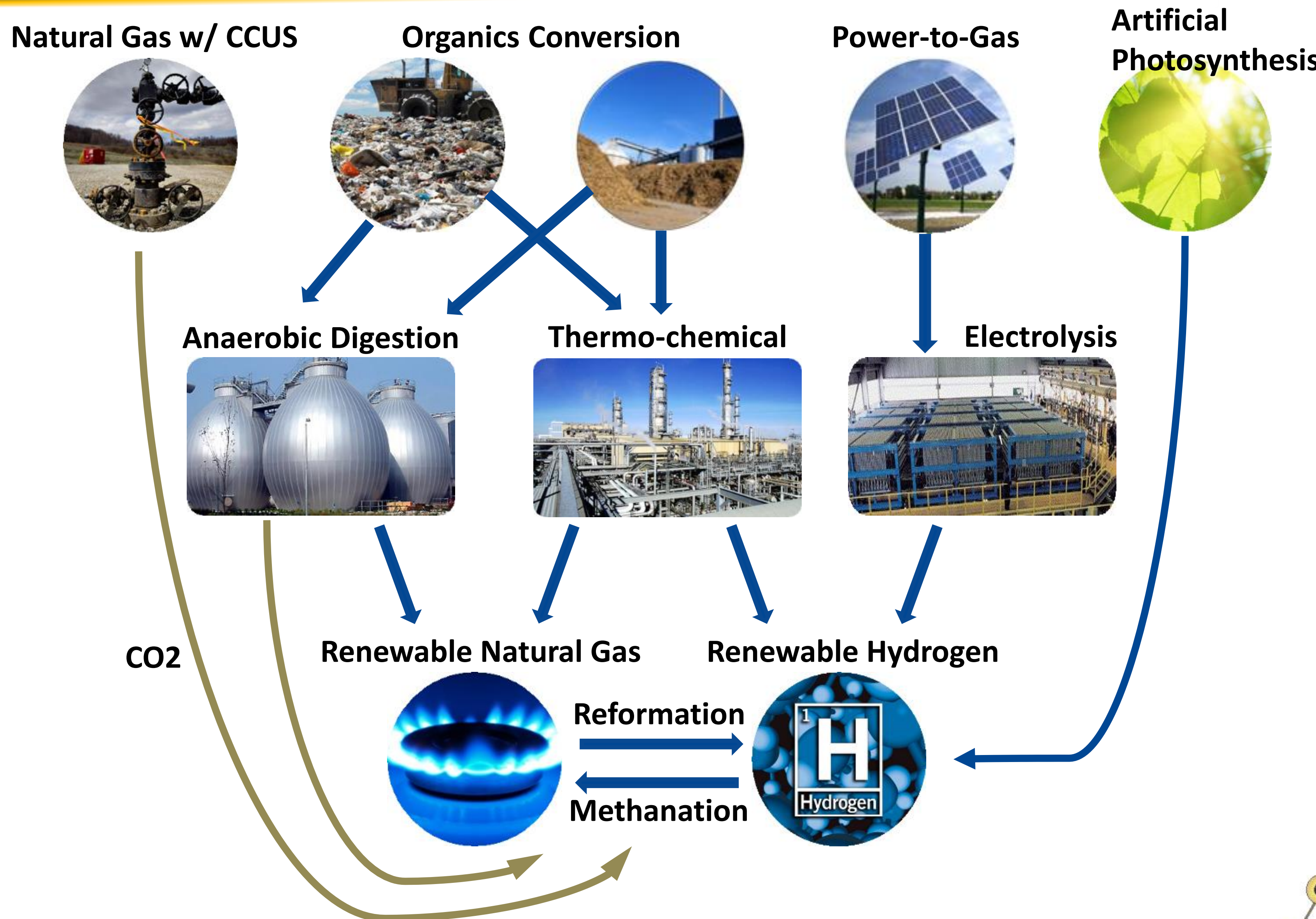
- **The current project seeks to assess the full production and delivery chain build out and cost over time**
  - **Quantitative**
  - **Time-phased**
  - **Focus on requirements to serve the evolving LDV population in the context of additional sources of demand for renewable hydrogen**
  - **Conditions needed for the sector to become self-sustaining**

- **Goal is to make visible key aspects of the renewable hydrogen production through delivery chain:**
  - **Help minimize cost and adverse environmental impacts of the build-out**
  - **Capture positive and negative learnings from early projects to guide process and policy improvements and build data on “as-built” costs**
  - **Provide a fact base to support investment analysis by value chain participants and incentive program development by state agencies**

- **Today’s presentation provides preliminary results of the ongoing analysis**

Overview and Summary

Renewable Gas Pathways



Renewable Hydrogen Roadmap for California

Technology Cost and Performance

- Electrolysis, AD, gasification
- Developer input + literature

Feedstock Cost and Availability

- Billion tons and UC Davis as baselines + H_2/CH_4 allocation
- Renewable electricity

Siting Constraints

- Footprint and emissions
- Zoning / access
- DAC screen
- Developer input

Renewable Hydrogen Demand Evolution

- CaFCP, CaSFCC and developer input
- Additional demand assessment (H2@Scale), UCI Ports RM

Siting Analysis -- Production and Delivery Chain Options

- Candidate sites by technology and grid location
- Least-cost build scenarios based on full production and delivery chai

Integrated Renewable Hydrogen Roadmap

- Spatial and temporal build-out scenarios (starting from existing and planned projects)
- High-level optimization and build sequencing
- Barriers and enablers + recommended actions
- Future research needs

Key Findings to Date

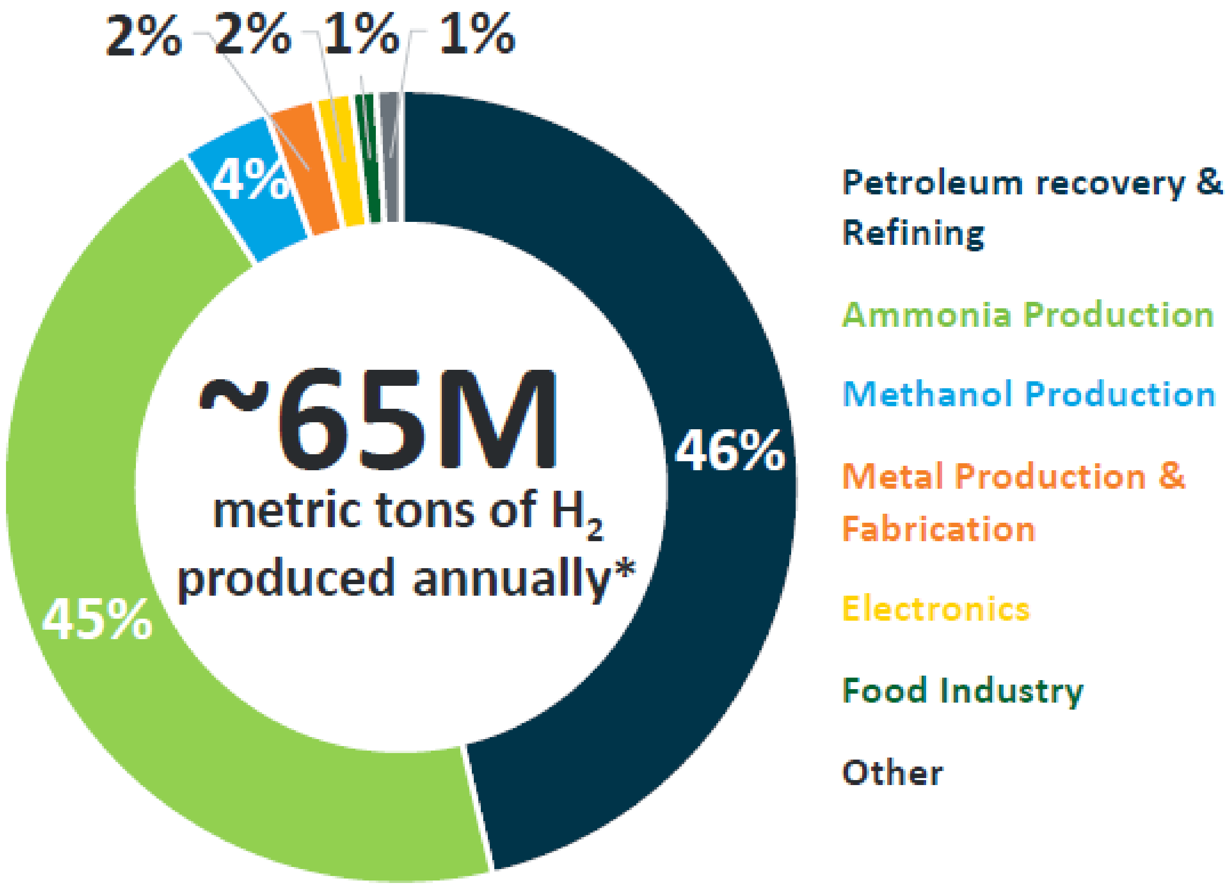
- RH2 demand could reach 350 million kg/yr by 2030 and 4,200 million kg/yr by 2050 (equivalent of about 25% of current vehicle fuel demand)
- Outlook on demand growth, LCFS prices and tight supply in conventional H2 market have led to significant investment announcements
  - 40 tons per day of new SMR / liquefaction capacity announced
  - Additional 5 – 10 tons per day of electrolytic hydrogen under development
  - Adequate supply through ~2022 (assuming biomethane supply is available)
- The general industry perspective is that price of dispensed hydrogen must reach fuel-economy-adjusted price parity with gasoline within 3 to 5 years ($6 - $8.50 per kg)
- The supply chain is shifting from gaseous to liquid transport and storage to accommodate larger station size for next generation stations and beyond

Key Findings to Date

- All primary RH2 production pathways (reformed biomethane, electrolysis and gasification) have the potential to compete in the market by the mid 2020's
  - Assuming LCFS prices remain robust
  - Organic waste mandates will ensure that the in-state organic feedstock will be developed – allocation among RH2, RNG and renewable liquids is uncertain
- A self-sustaining hydrogen transportation sector appears to be possible by the mid to late 2020's assuming that progress on cost reduction meets base-case projections and LCFS credit prices remain above ~$100 - $150/credit
- An LCFS credit price support mechanism and continued support for early-market and connector stations will likely be needed to ensure a smooth acceleration of FCEV market growth
- Impacts of mixed liquid and gaseous supply chain needs further assessment

Renewable Hydrogen Demand and Supply Analysis

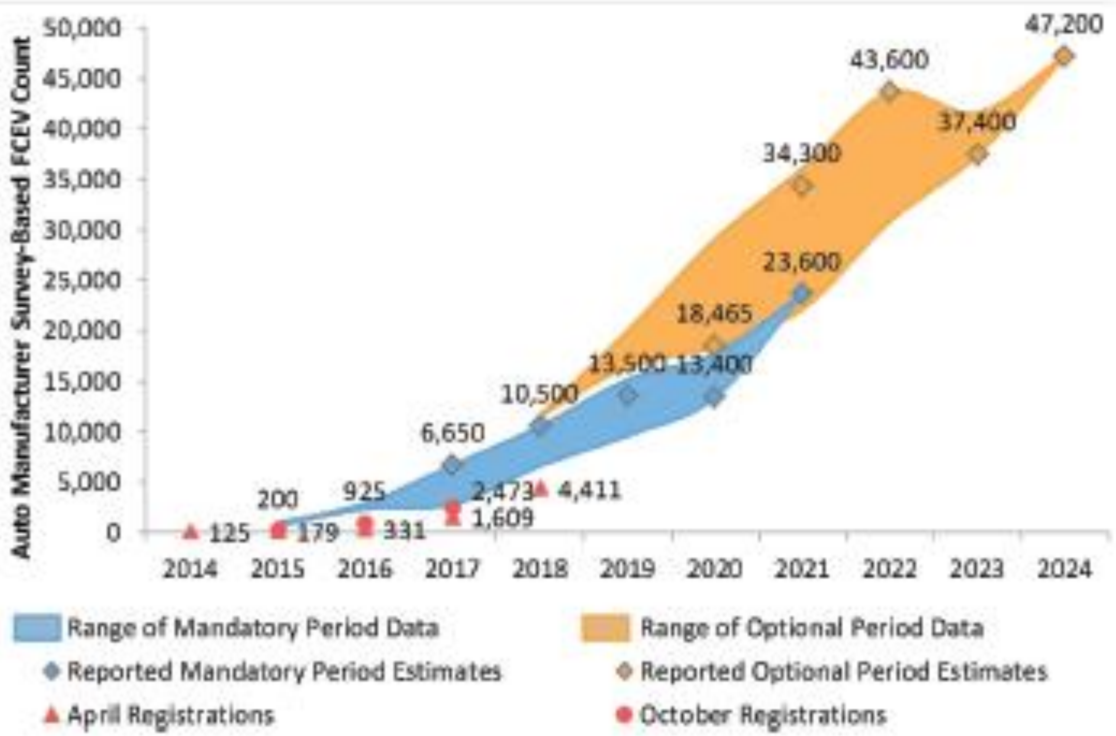
Global Hydrogen Production and Demand



Source: (Satyapal 2017)

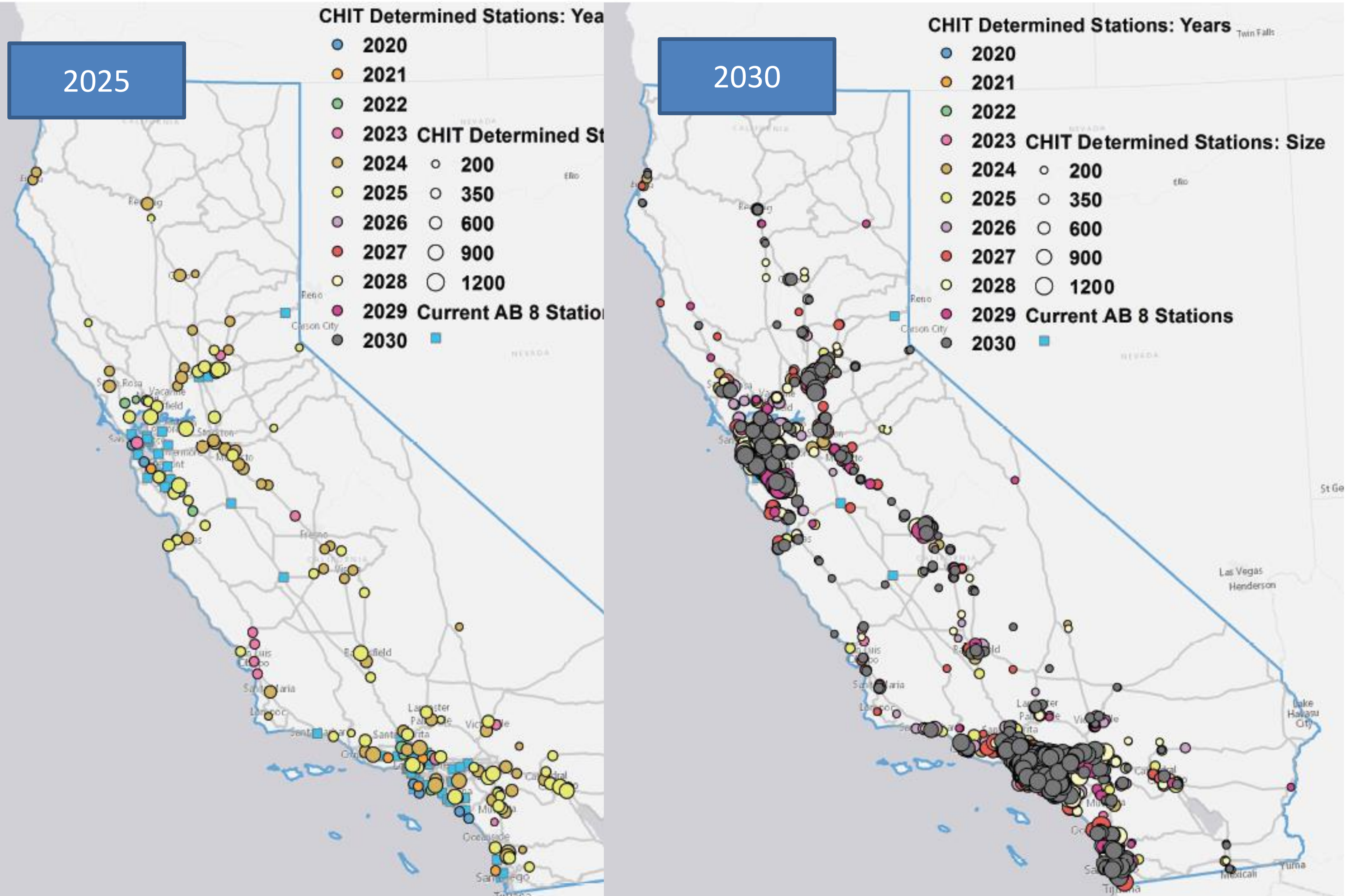
Hydrogen Vehicles will Drive New Demand

FIGURE ES3: CURRENT AND PROJECTED ON-ROAD FCEV POPULATIONS AND COMPARISON TO PREVIOUSLY COLLECTED AND REPORTED PROJECTIONS



Interim Results

CARB Vision Scenario Final Results



Other Transportation Demand Potential

- Provide zero emissions fuel to difficult end-uses

Shipping

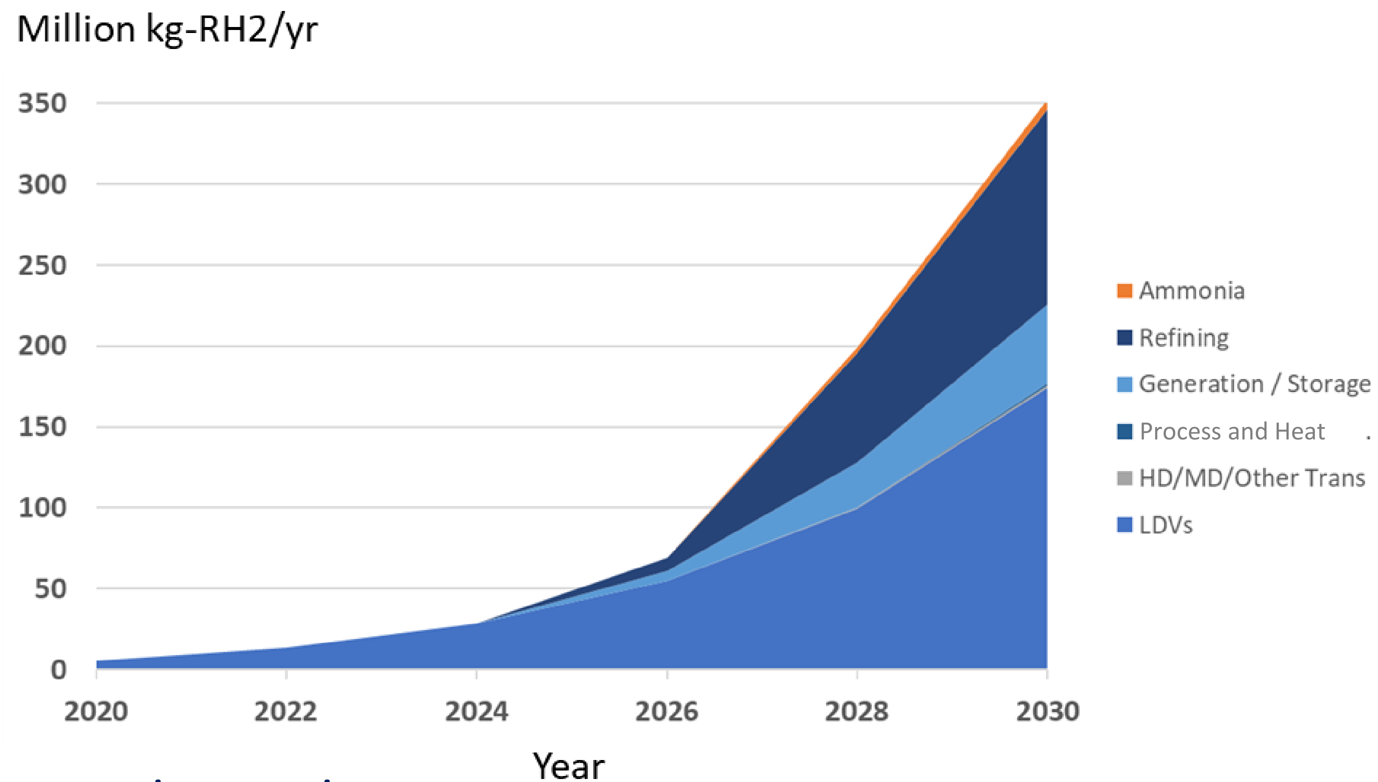
Aircraft


Fuel Cell Trains & Locomotives

Fuel Cell Buses

Toyota Fuel Cell:
Zero Emissions Big Rig

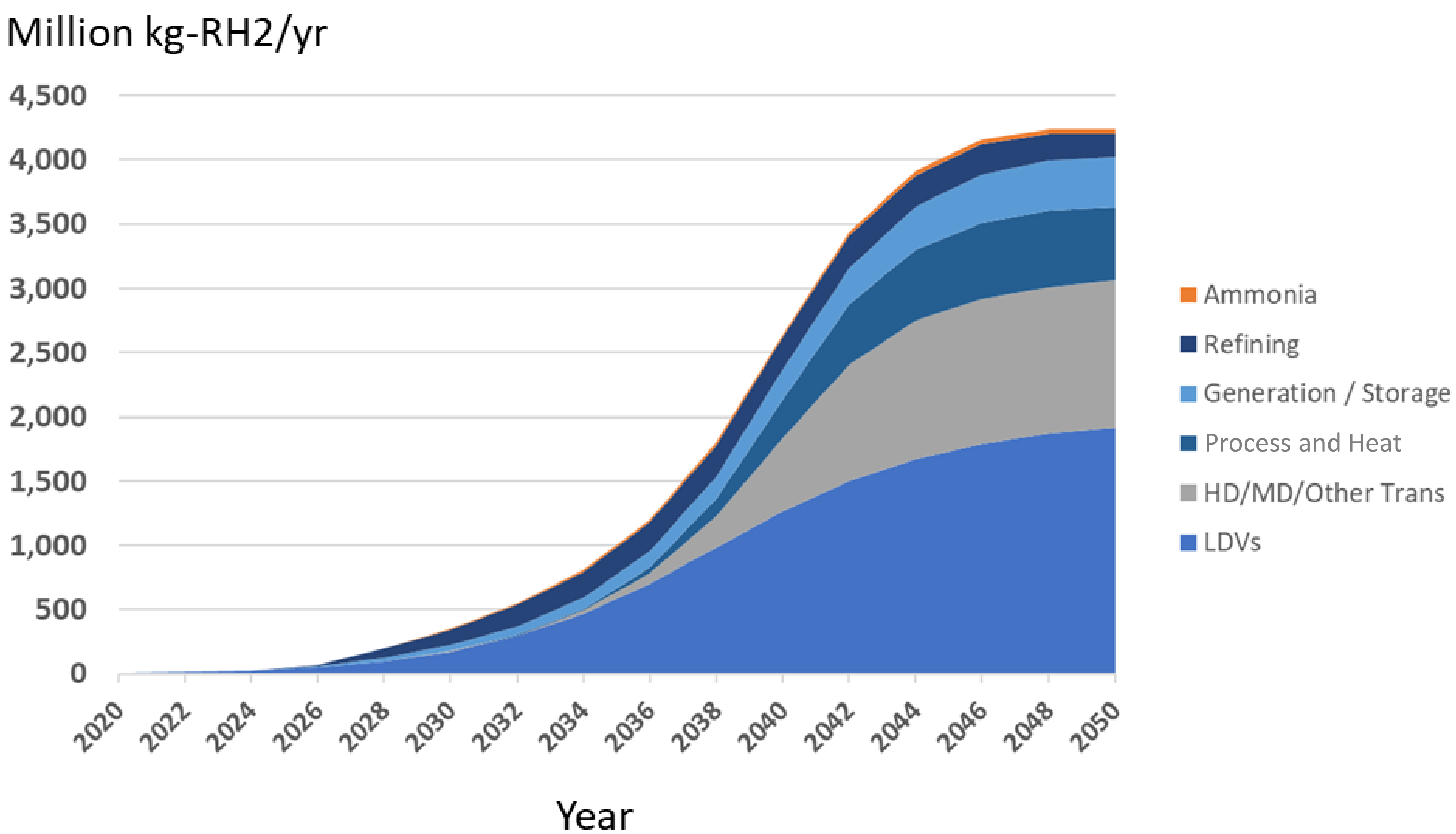
High-Case California Renewable Hydrogen Demand to 2030



High-case scenario assumptions

- **Light-duty: 1 million FCEV by 2030 with 25% ultimate share**
- **Other Transportation – Based on Vision 2.1 with 50% FCEV share of MD/HD and 20% of remaining off road**
- **Heating and Process – RH2 assumed to serve 10% of current natural gas demand by 2050**
- **Generation and Storage – Based on RESOLVE scenarios with P2G replacing 50% of planned storage and geothermal**
- **Refining – Continual increase of renewable hydrogen fraction to 100% beginning in 2025**
- **Ammonia – Continual increase in renewable fraction of anhydrous ammonia to 100%**

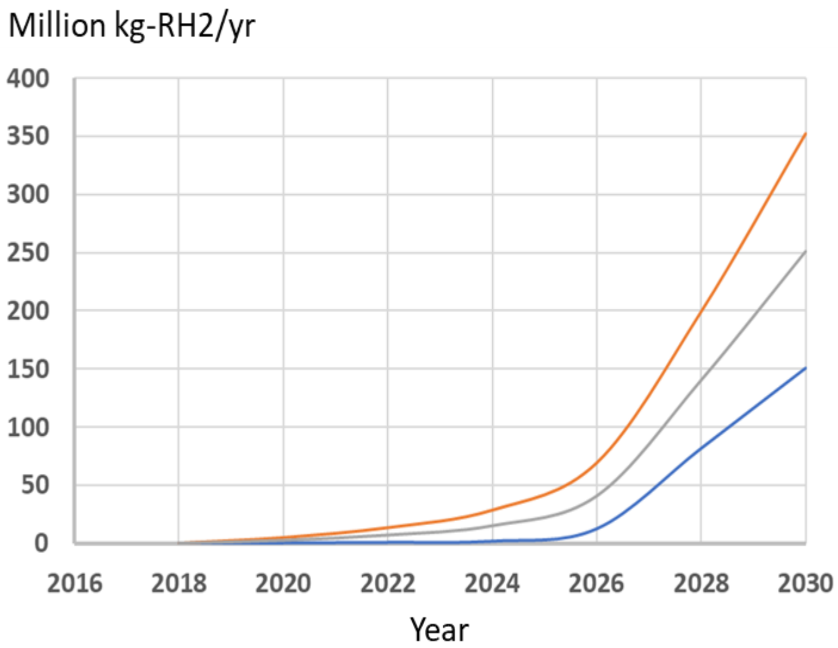
High-Case California Renewable Hydrogen Demand to 2050

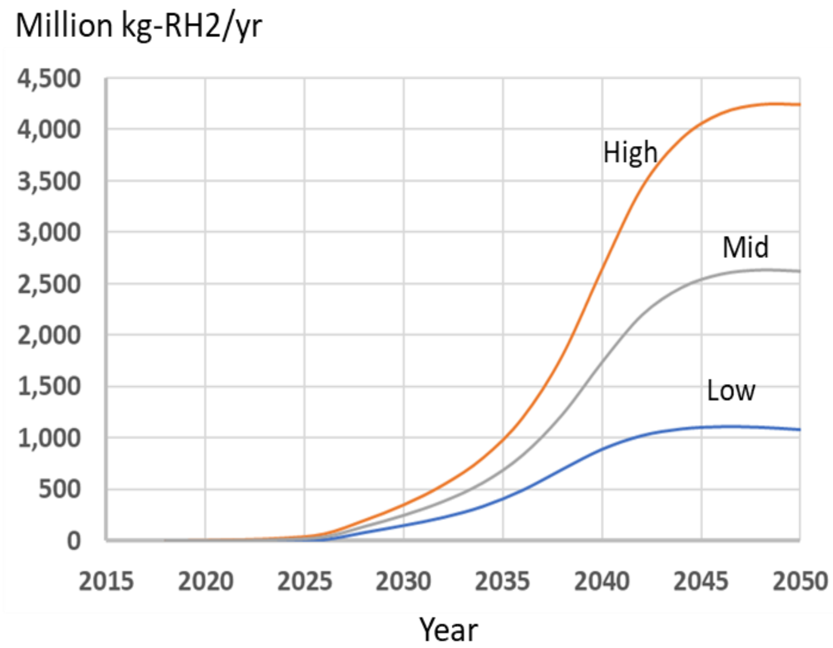


Interim Results

Full Set of RH2 Demand Scenarios

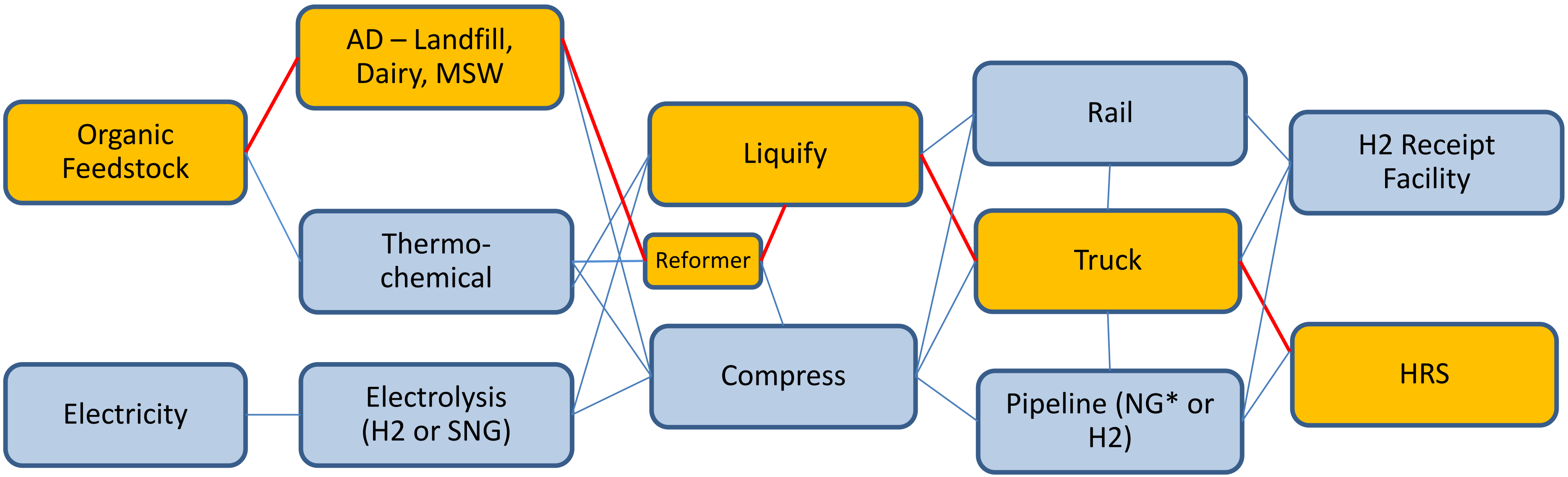
Preliminary





Interim Results

RH2 Delivered Cost Analysis



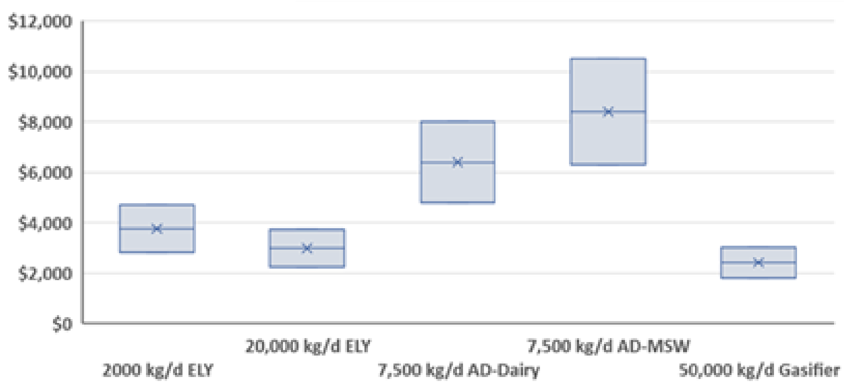
Cost Modeling

- **Incremental levelized cost of hydrogen calculated at each step**
- **Production cost modeling developed with H2A and supply chain costs with HDSAM (DOE tools)**
- **Input assumptions on technology cost and performance from the Technology Characterization task of this project**

Capital Cost Forecasts

Capital Cost
per kg/d nameplate

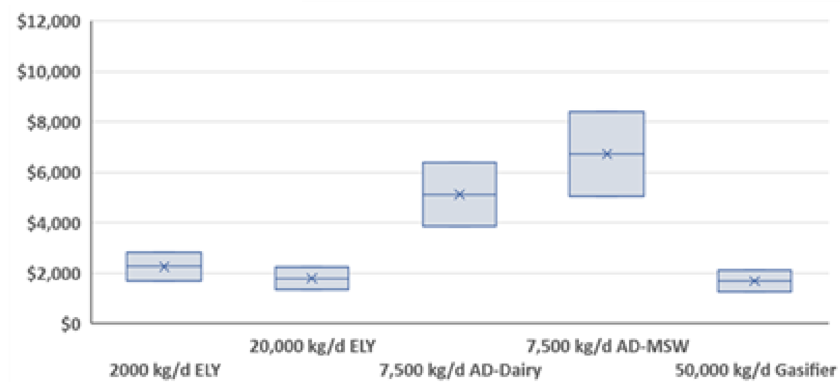
Current



Technology and Capacity

Capital Cost
per kg/d nameplate

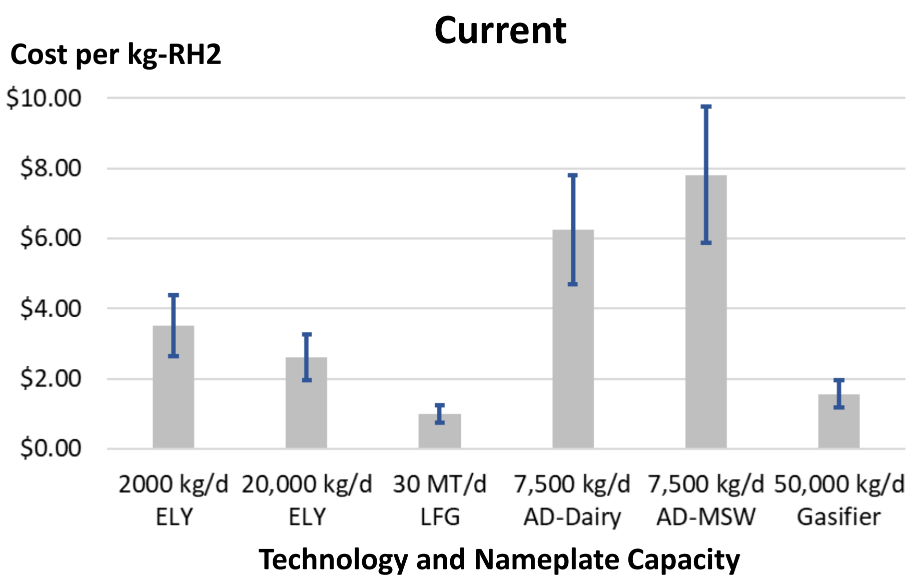
2030

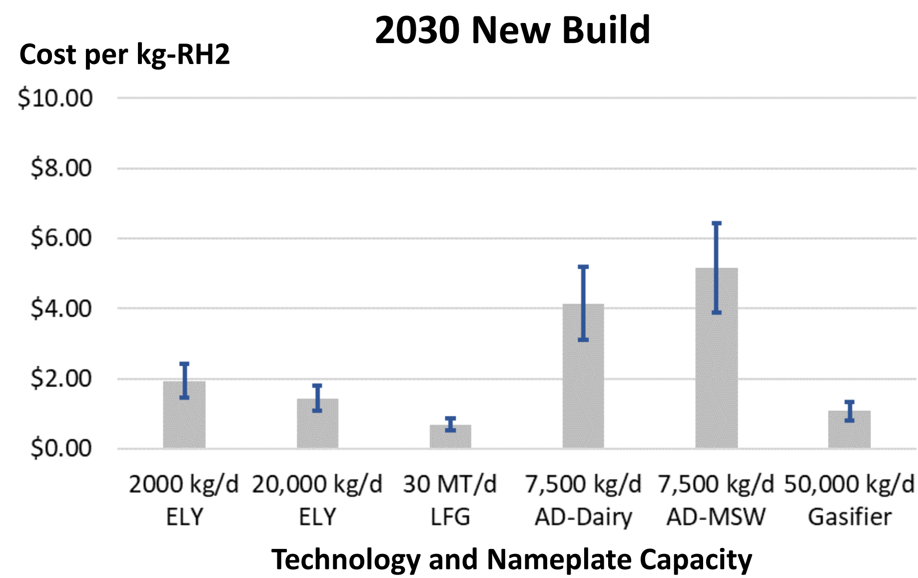


Technology and Capacity

- **Electrolyzer costs forecast to decline ~40% by 2030 (base case)**
- **AD and Gasification costs forecast to decline ~20% by 2030**
- **Gasification costs forecast to decline ~25% by 2030**
- **Efficiency improvement on the order 10%**

Conversion Costs (RH2 production cost excluding feedstock)



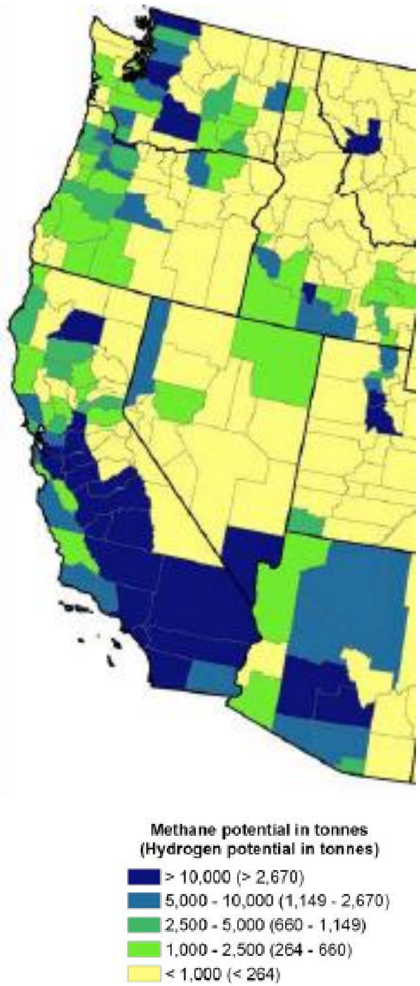


Note: AD and LFG pathways include cost of SMR

Assumptions

- **All equity financing with 10% after tax IRR**
- **AD pathways includes the cost of reforming biomethane using H2A SMR cost model scaled to 30 RH2 tons per day**
  - **$400/kw-th and 72% efficiency current case**
  - **$300/kw-th and 80% efficiency in 2030**
- **Additional detail in technology characterization report**

Organic Feedstock Cost and Quantity Assumptions



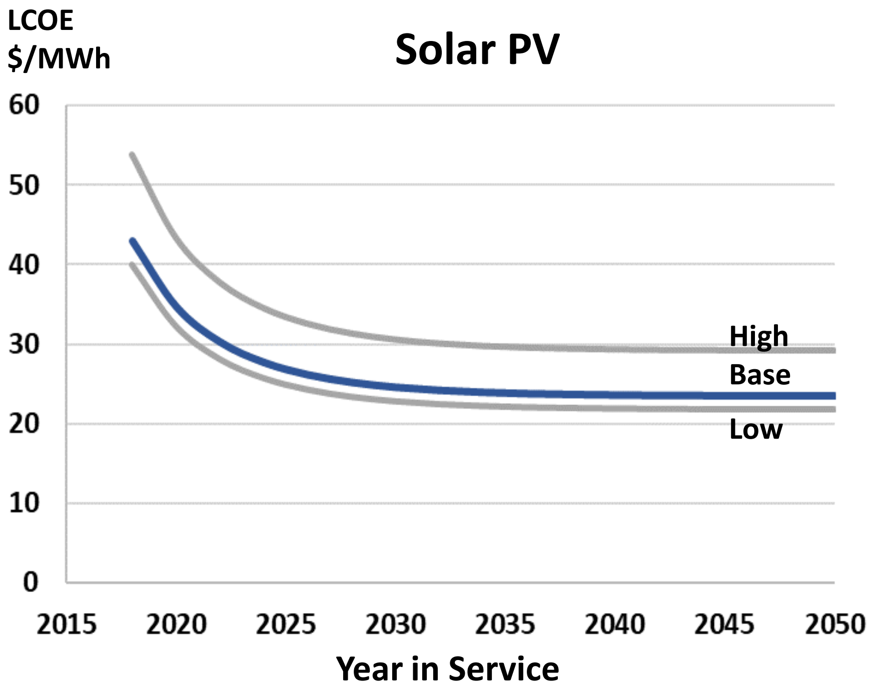
Feedstock	Max RH2 Feedstock[1]	Cost Range	Allocation
Landfill Gas	43 x 10^6 GJ/yr	\$10 - \$15 \$/MMBtu	• Base case is 50% to H2
OFMSW	16 x 10^6 GJ/yr	(\$40) – (\$80) \$/dry ton	• Base case is 50% to H2
Dairy Manure	11 x 10^6 GJ/yr	\$0 - \$2 \$/MMBtu	• Base case is 50% to H2
Forest and Crop Material	150 x 10^6 GJ/yr	\$30 - \$100 \$/ dry ton	• Base case is 80% to H2
Energy Crops	--	--	• Under assessment

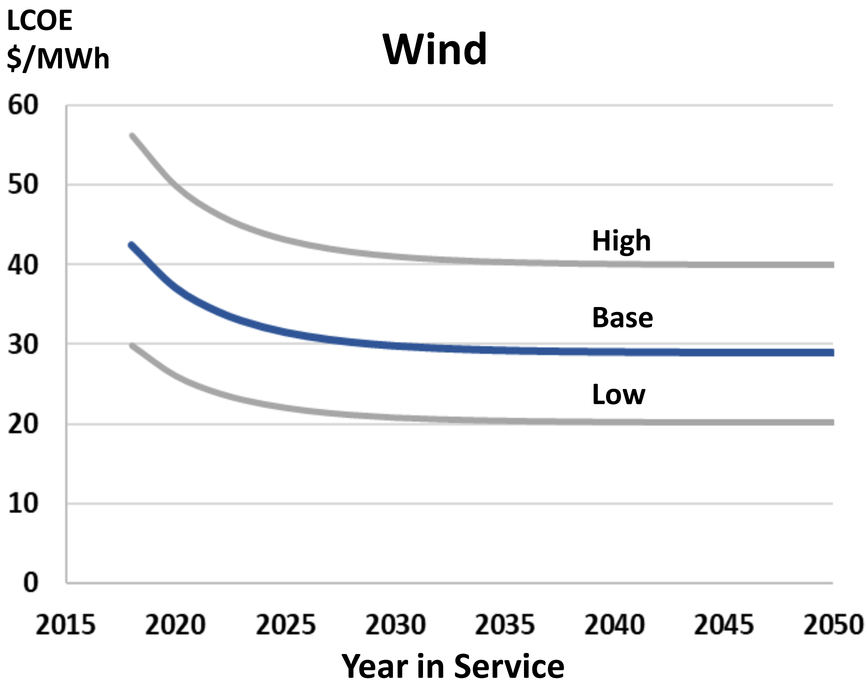
1) Assumes in-state potential augmented by equal amount of out-of-state supply and multiplied by the allocation factor

Total RH2 potential from organic feedstock ~2,000 million kg/yr based on assumed allocations

Interim Results

Solar and Wind New-build Self-generation Costs

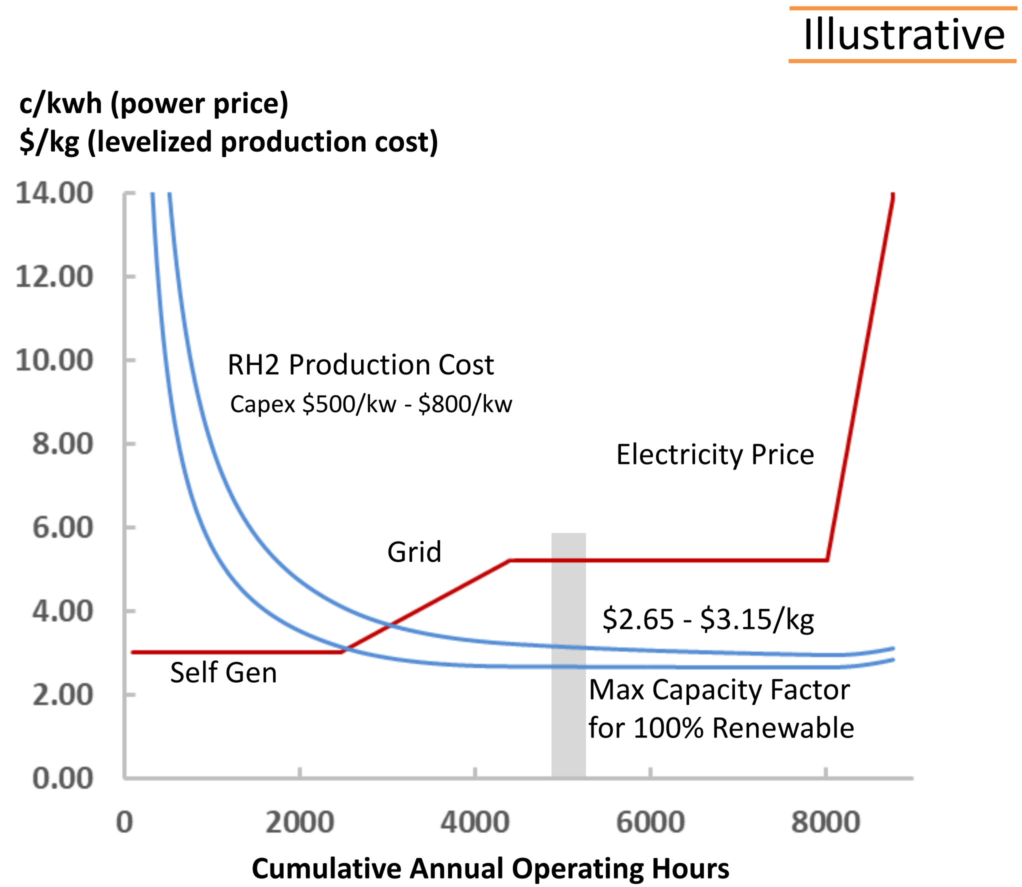




- Low and mid cases based on Lazard's Levelized Cost of Energy, Version 12.0
- High based on CPUC RESOLVE model wind and solar cost assumptions

Interim Results

Electrolytic Hydrogen Production Cost in 2030 Timeframe



- **Representative case of self-generated solar augmented with wind PPA or spot purchases**

Interim Results

Siting Analysis Approach

H2 Fueling Station Heat Maps

Local-scale Electrolysis
- Co-located with hydrogen refueling station – use existing heat maps from ARB

Electric Transmission
Gas Transmission
Topography / Land Use
Biomass Resources
Roads and Rail
Population density

Assign attributes to each cell

Apply Exclusion Criteria
- Mountainous areas
- Protected lands
- Residential areas

If not excluded, then evaluate for each technology

Central Electrolysis
- In solar or wind resource area, or on electric transmission line
- Highway and/or rail access
- 10 acre site availability

Dairy AD
- Anchor herd of 5000 milking cows
- Proximate to natural gas transmission

OFMSW (Food) AD
- Existing WWTF, permitted refuse facility or existing refuse route
- Proximate to natural gas transmission

SMR
- Proximate to natural gas transmission
- Highway and/or rail access
- 10 acre site availability

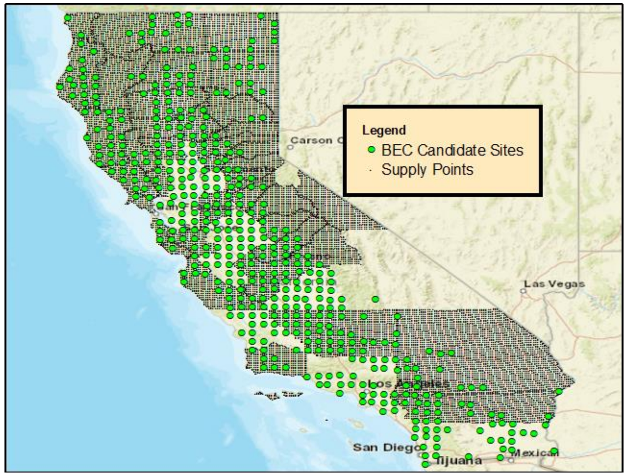
Gasification
- Proximate to biomass resource
- Highway and/or rail access
- 10 acre site availability

For each cell and each technology:

If min. criteria met, then assign score, else, not a candidate site

Scoring based on cost and community impacts

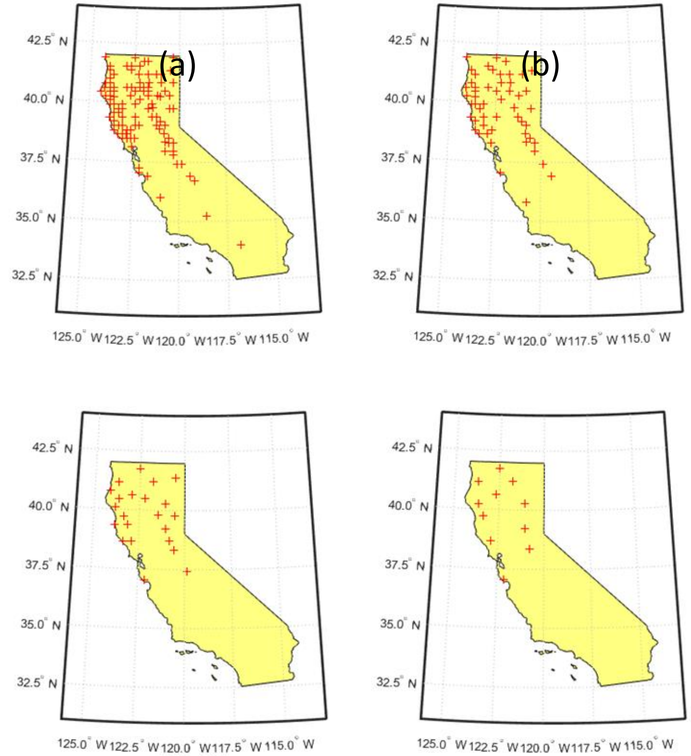
Example Siting Analysis Result



BEC plant sites that minimize transport costs at roadside collection costs of $100/dry-ton

100 tons/day

200 tons/day

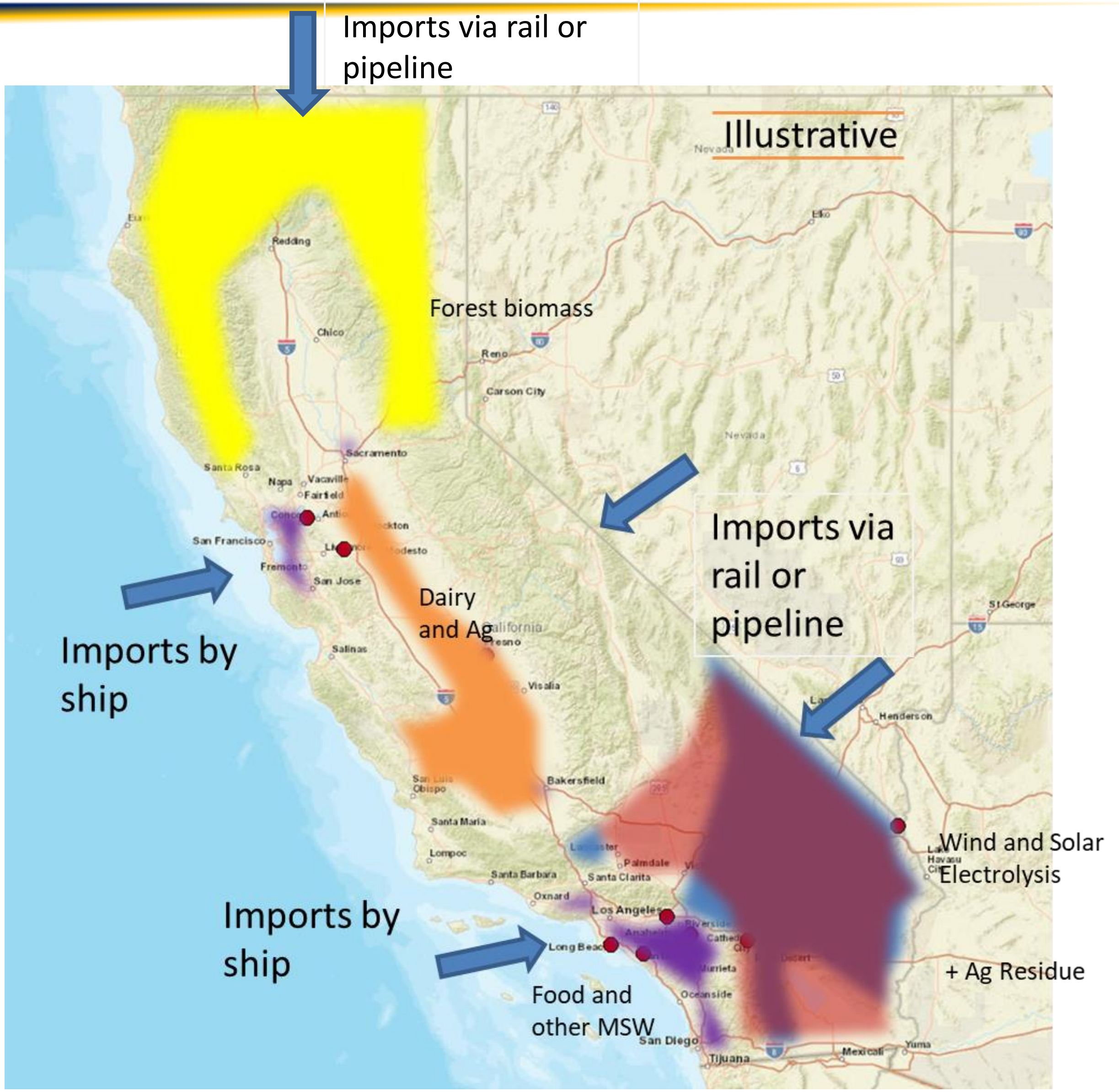


480 tons/day

960 tons/day

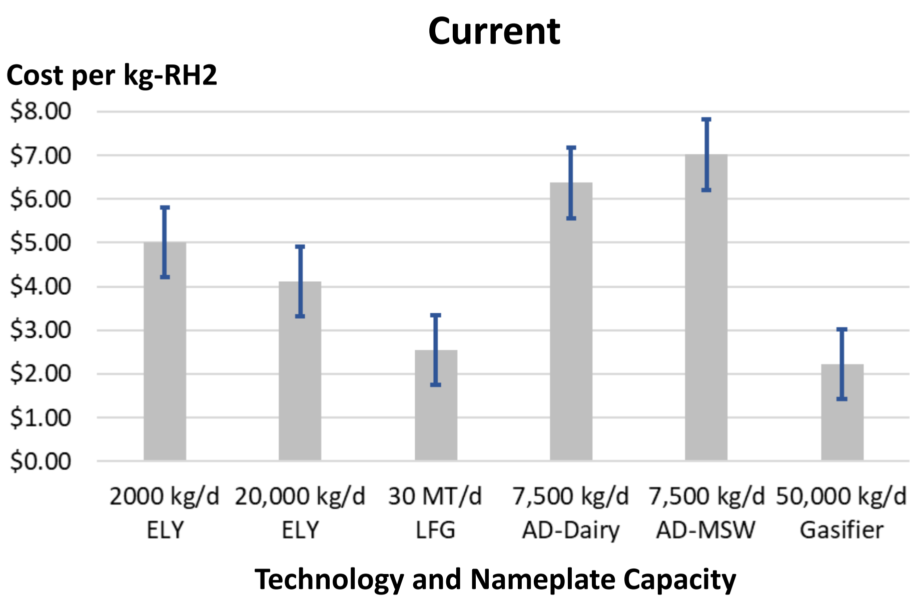
- **Optimization algorithm places gasification plants to available locations based on total demand and facility size to minimize cost of combined road and rail delivery to demand areas**
- **Additional overlay restricting coastal areas and applying disadvantaged community scoring to be added**

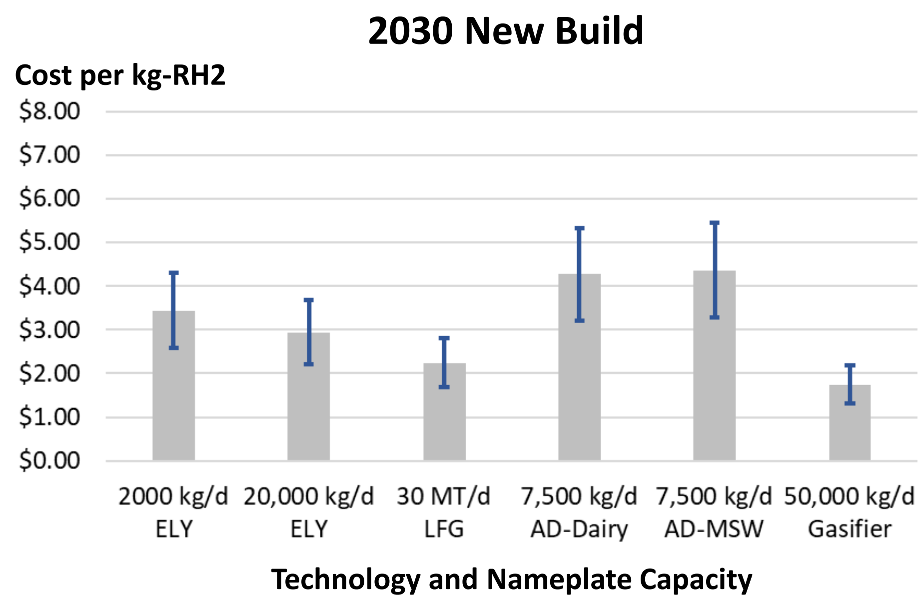
Primary Resource Areas for RH2 Production



Interim Results

Unsubsidized Cost of Hydrogen at Plant Outlet

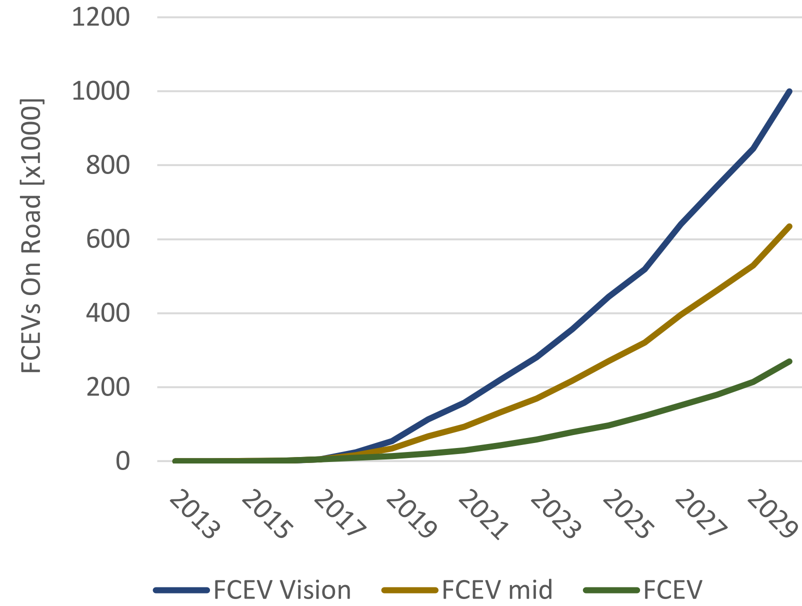


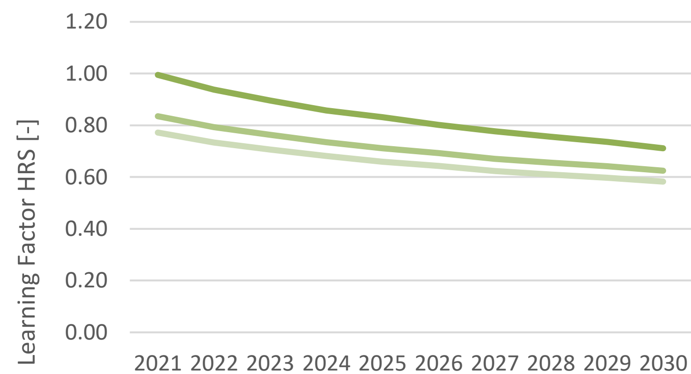


Interim Results

Plant Gate to Customer

- **Key inputs and Assumptions**
  - **Demand**
  - **Liquid supply chain assumed for new build**
  - **Technology Learning Rates**
    - ✓ **HRS → 10%**
    - ✓ **LH2 Terminal → 8%**
  - **HRS utilization**
    - ✓ **NorCA and SoCA = 70%**
    - ✓ **Rest of State and Connectors = 40%**
  - **Percent of HRS that are Connectors**
    - ✓ **5%**
    - ✓ **Connector Mean Demand = 100 kg/d**
  - **Terminal Size = 15 ton/d**
  - **Cost information from US DOE H_2 Delivery and Scenario Analysis Model (HDSAM)**
  - **Capital Recovery Factor HRS = 0.16**
  - **Capital Recovery Factor LH2 Terminal = 0.12**

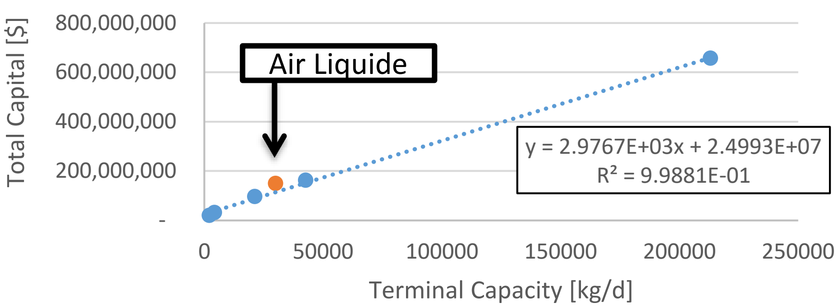


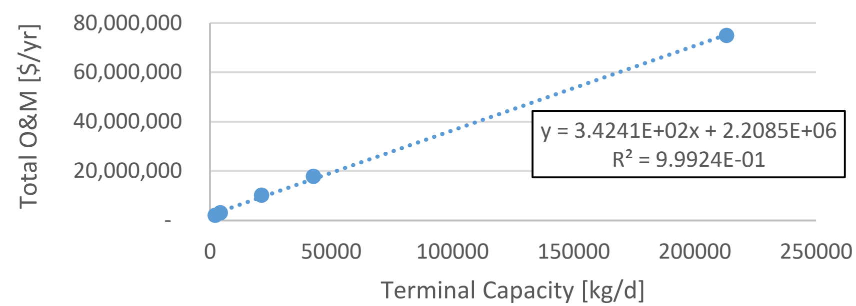


Interim Results

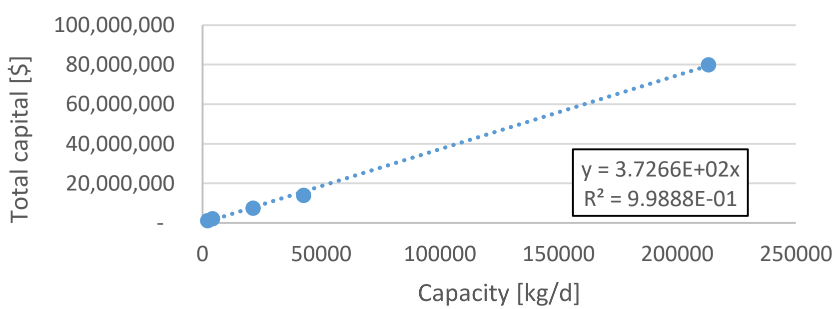
Plant Gate to Customer

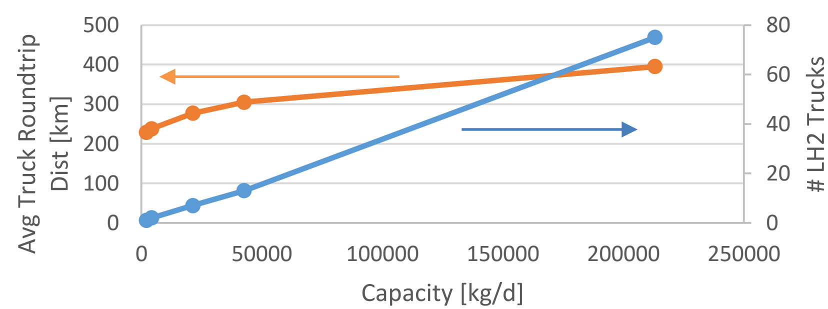
- **Liquid H2 Terminal (from DOE HDSAM)**





- **Delivery (from DOE HDSAM)**

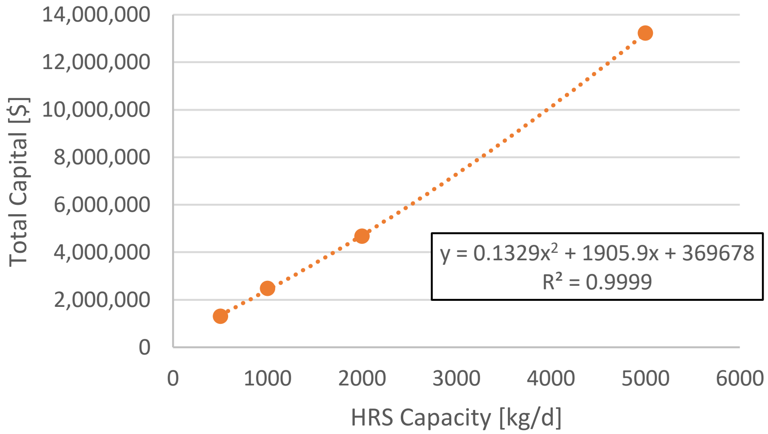


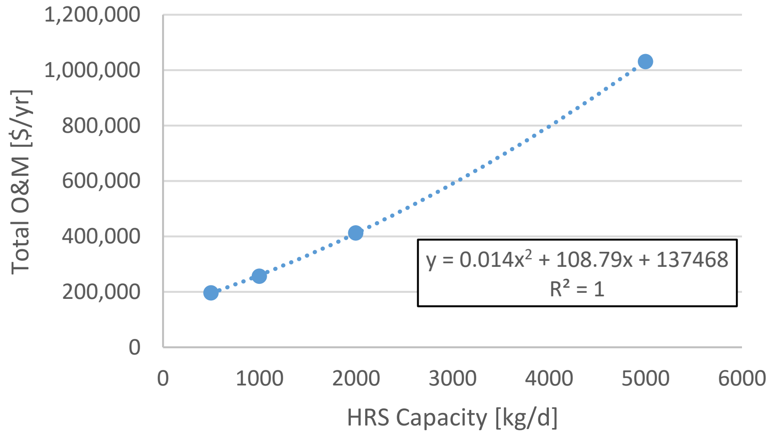


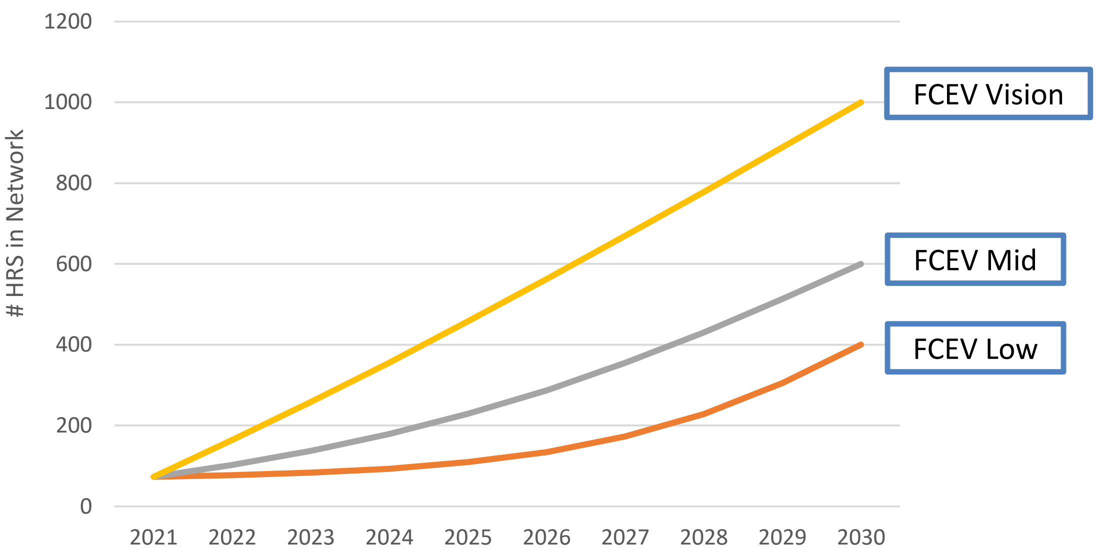
Interim Results

Plant Gate to Customer

- **Hydrogen Refueling Station (from DOE HDSAM)**



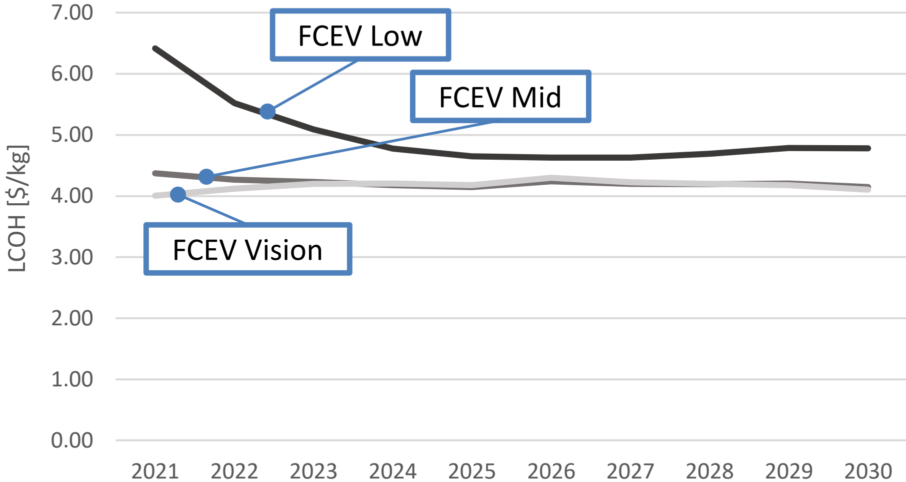


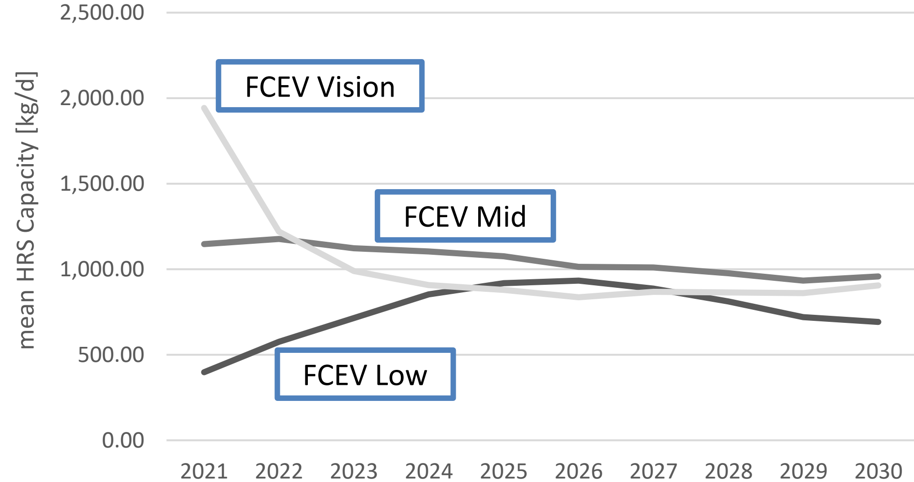


Interim Results

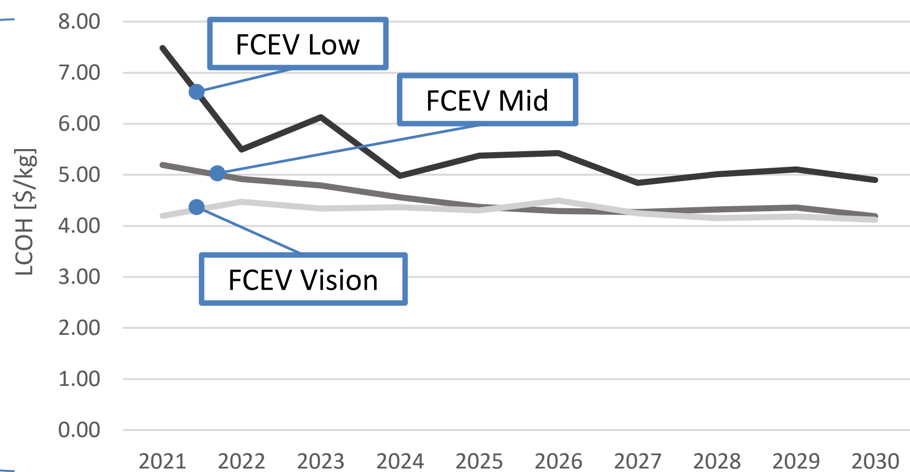
Plant Gate to Customer

- **Results – Ideal LH2 Terminal Roll out**





Unideal Terminal Deployment Scenario



Interim Results

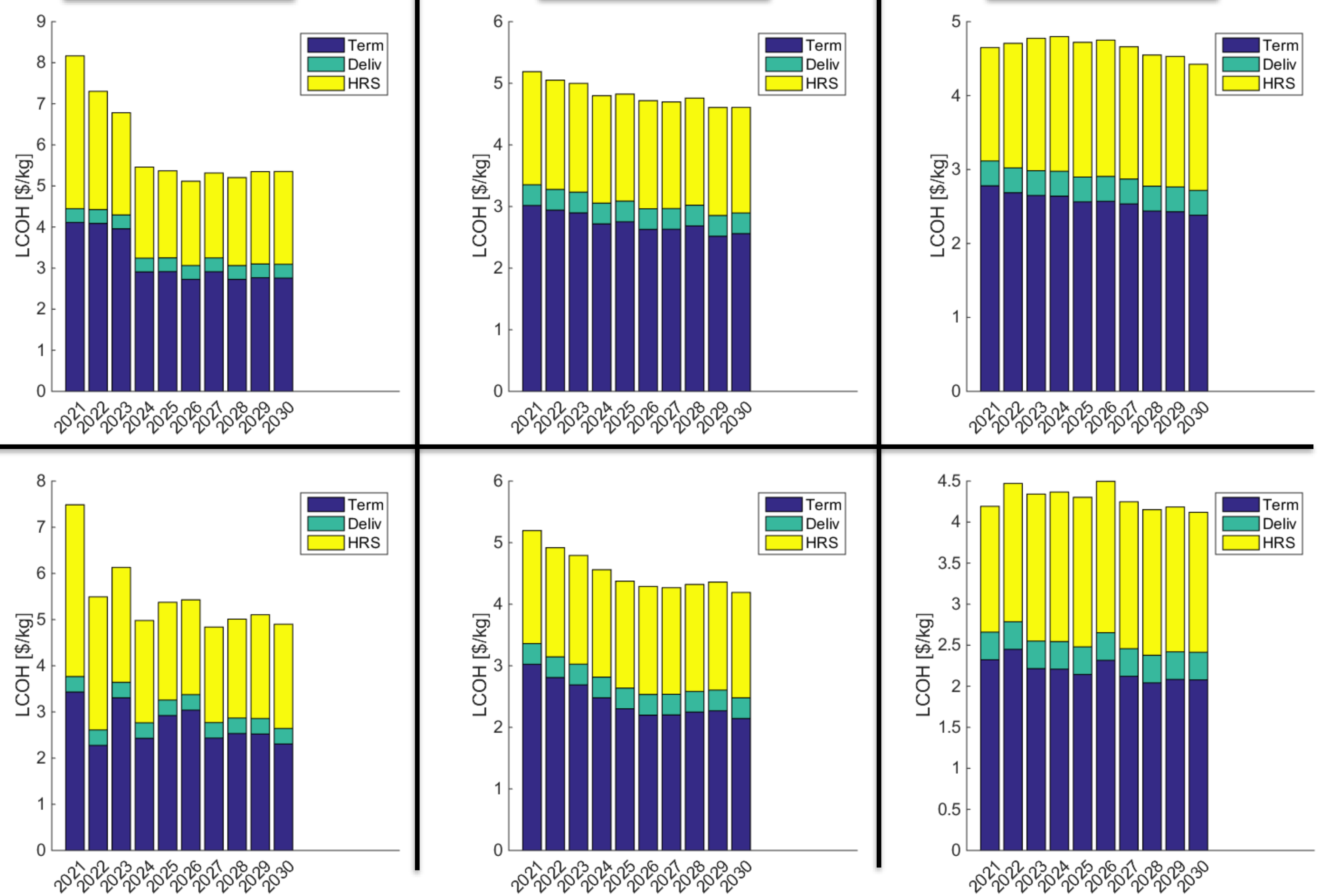
Plant Gate to Customer

Parameter Sensitivity

FCEV Low | FCEV Mid | FCEV Vision

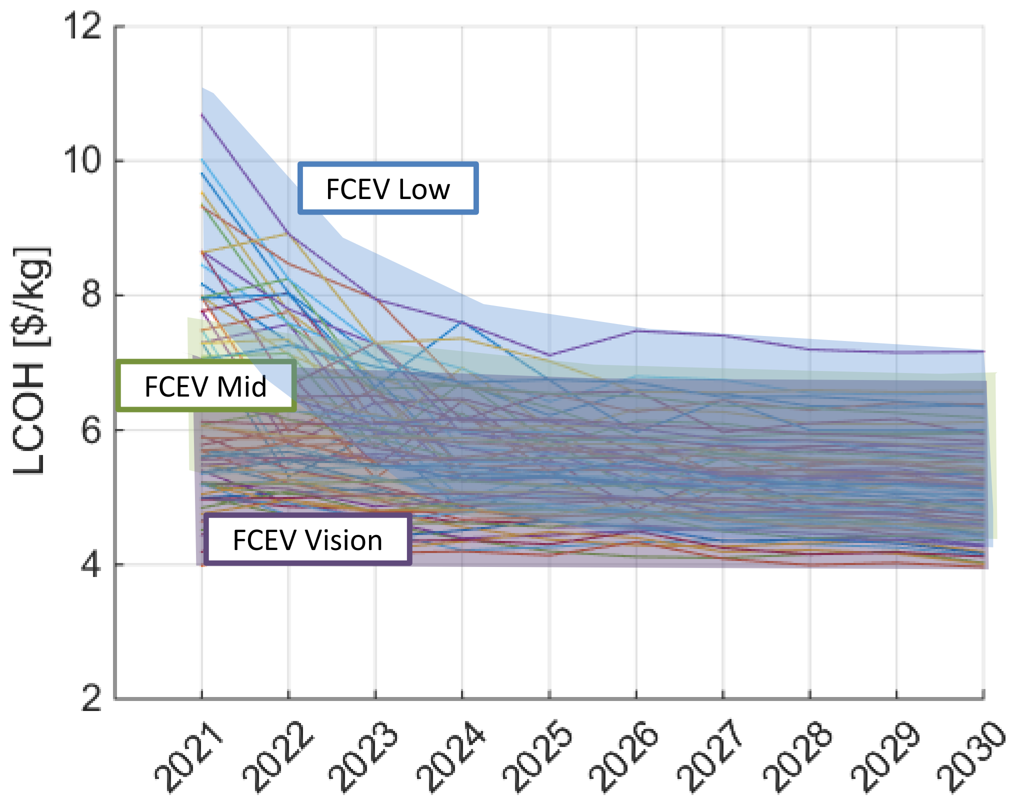
70% HRS Utilization
Terminal Size 15 t/d

70% HRS Utilization
Terminal Size 30 t/d



Plant Gate to Customer

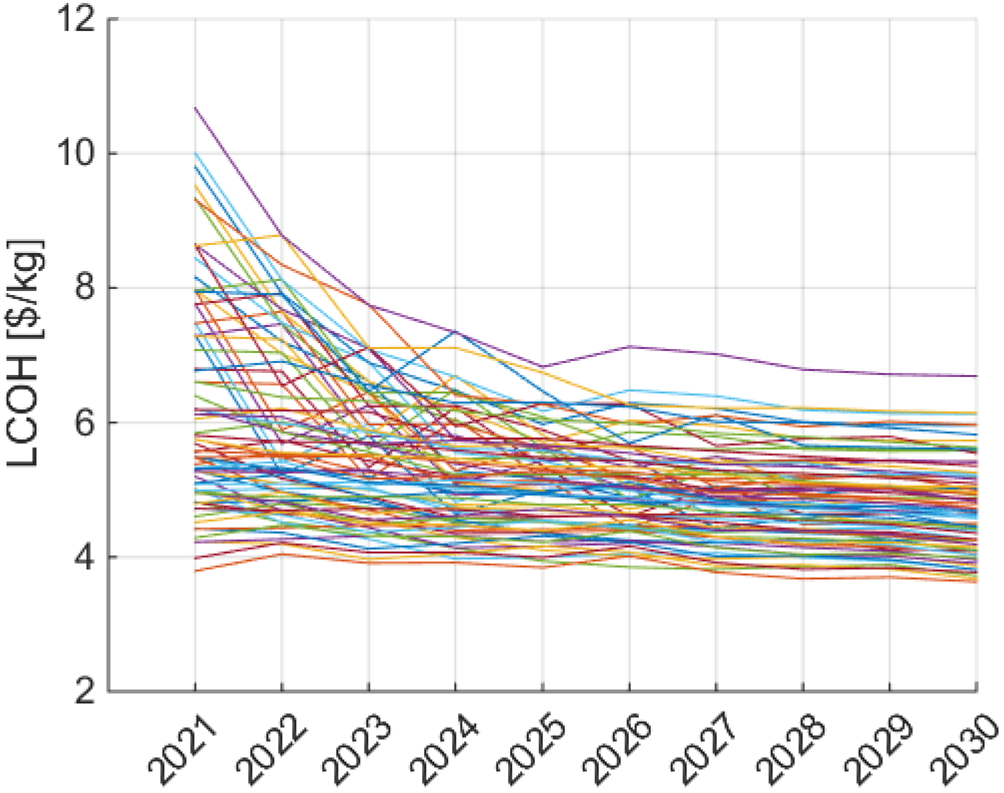
- **All Sensitivities together**



Interim Results

Plant Gate to Customer

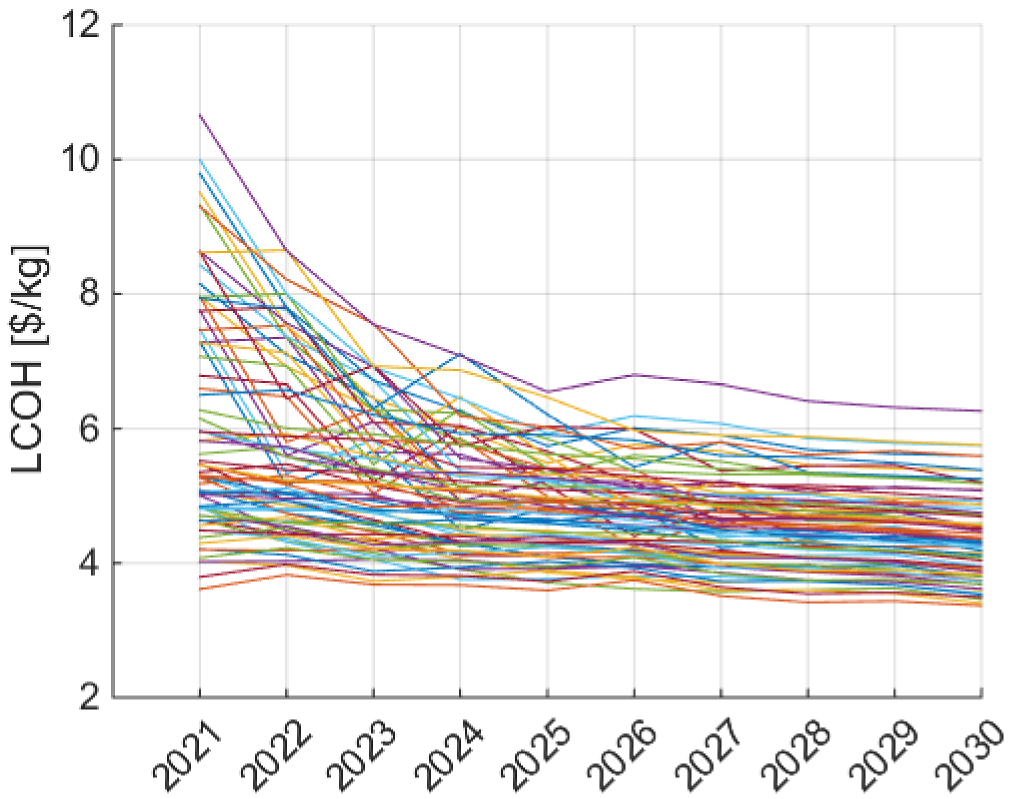
- **Increase learning rates by 50%**



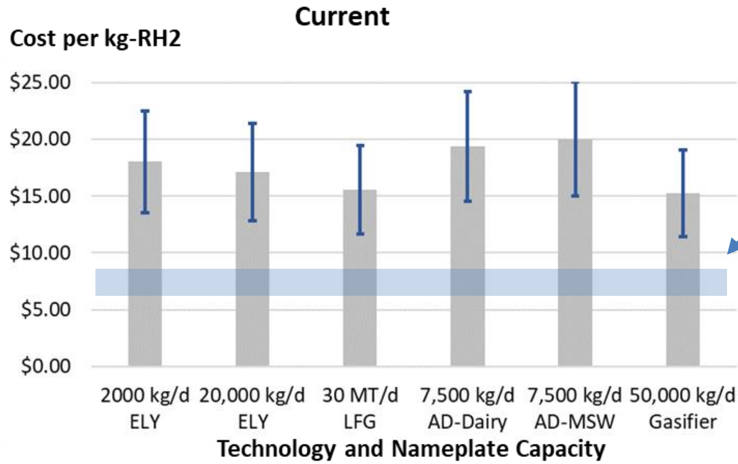
Interim Results

Plant Gate to Customer

- **Increase learning rates by 100%**

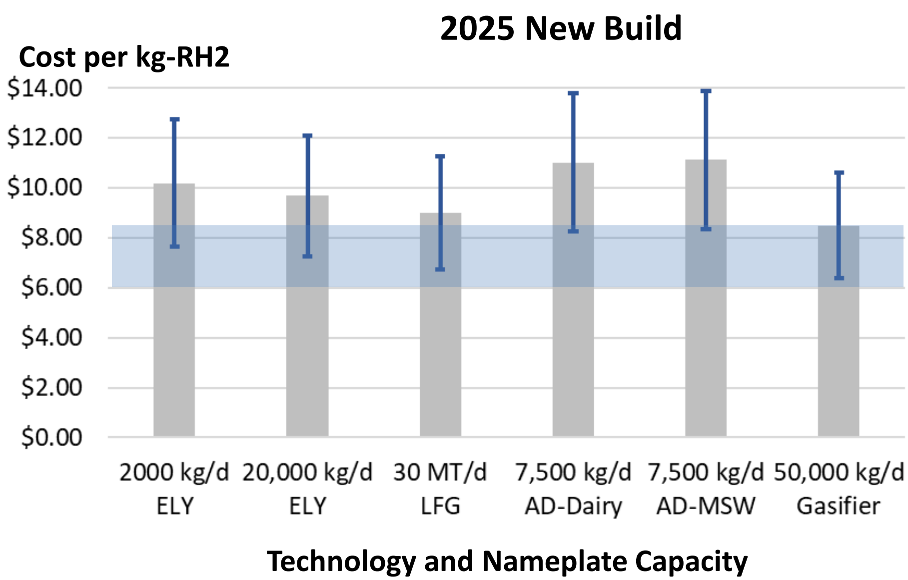


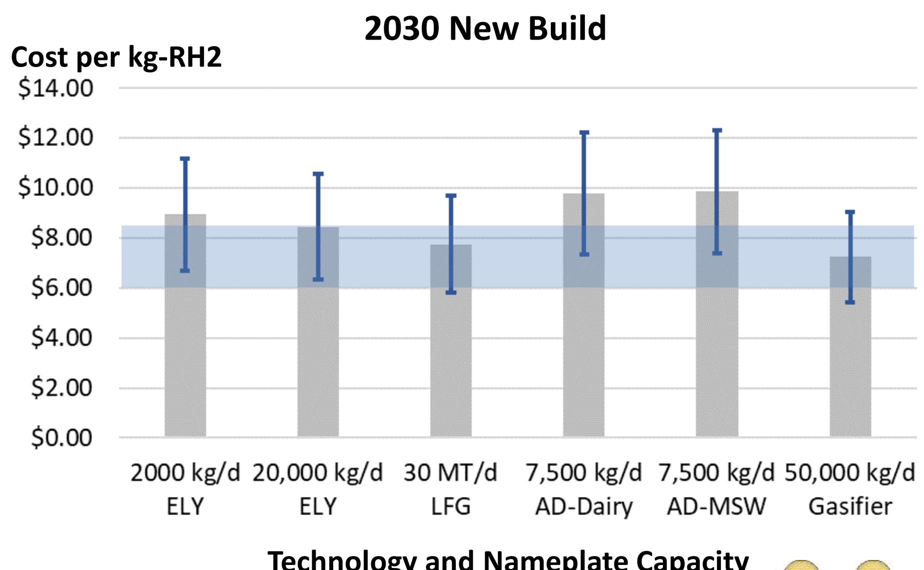
Full Dispensed Cost of RH2 without Credits



Shaded band indicates fuel-economy-adjusted parity with gasoline ($6 - $8.50 /kg)

- Gasoline $3.3/gallon +/- $0.50 (5 year average)
- Fuel economy ratio 2 to 2.5

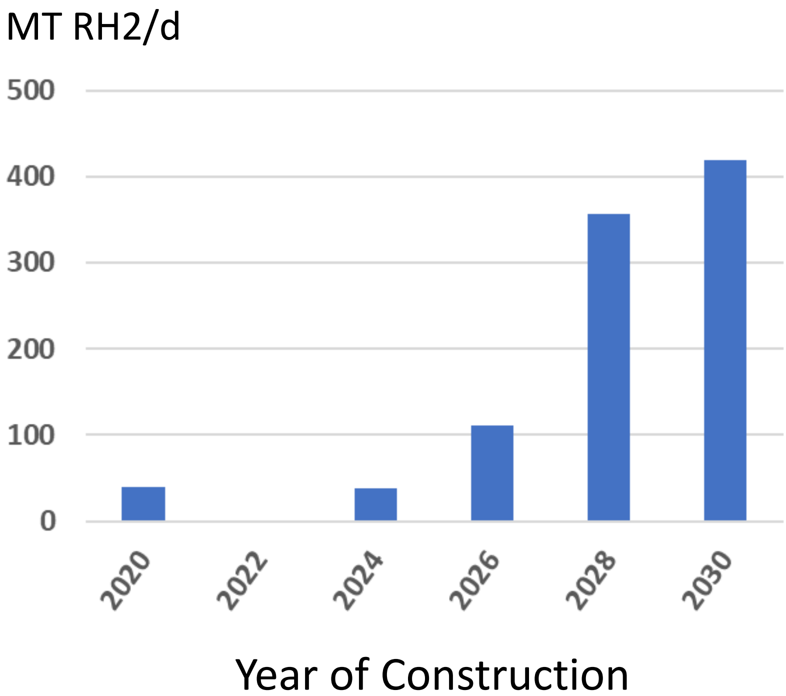


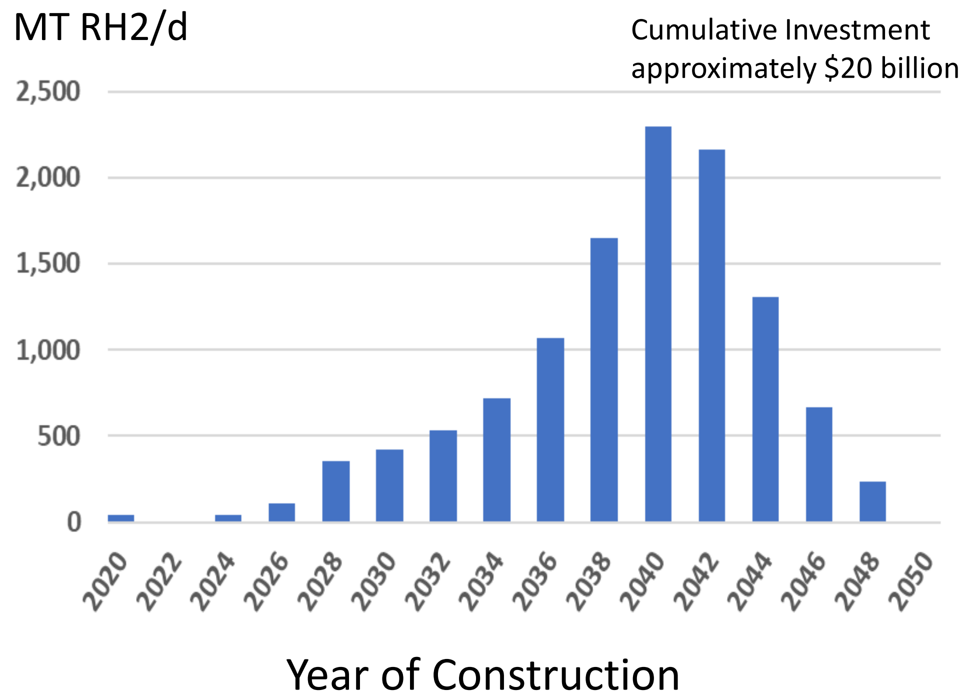


Interim Results

Build-out Needed to Meet Demand

Required Annual Additions in RH2 Production Capacity (Actual)
Transportation Only High Case

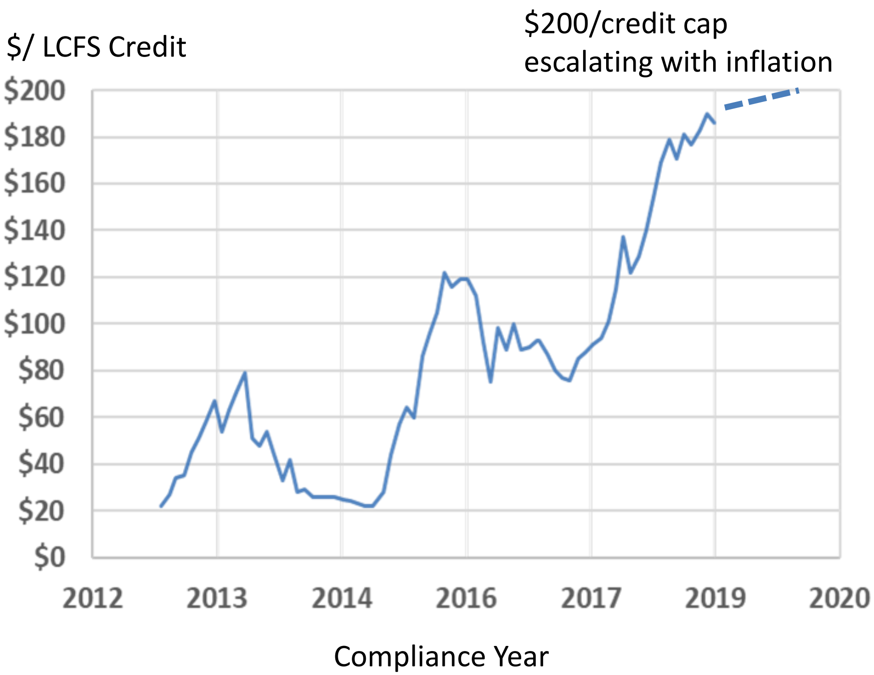


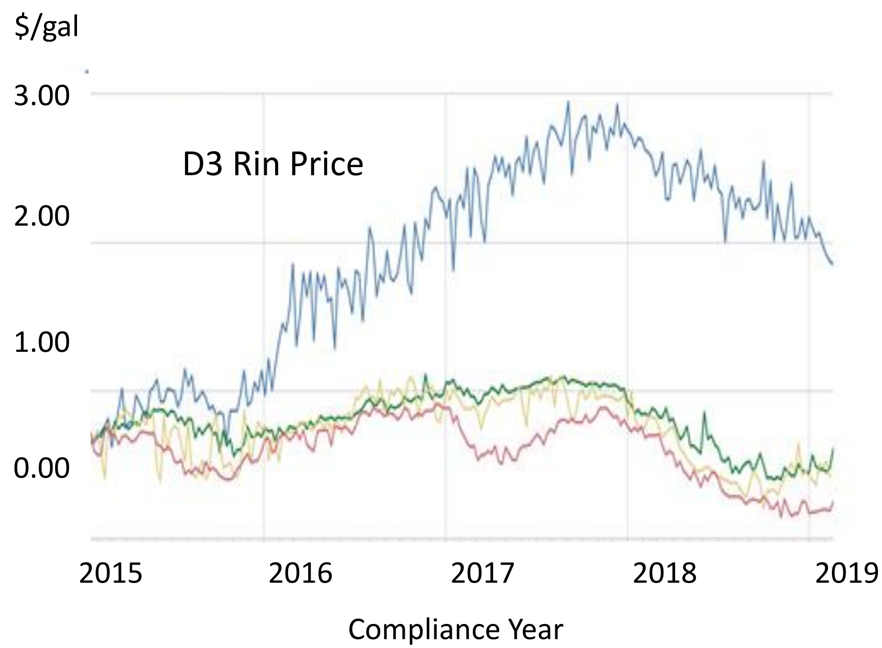


Getting to a Self-Sustaining Renewable Hydrogen Sector

Role of Credits

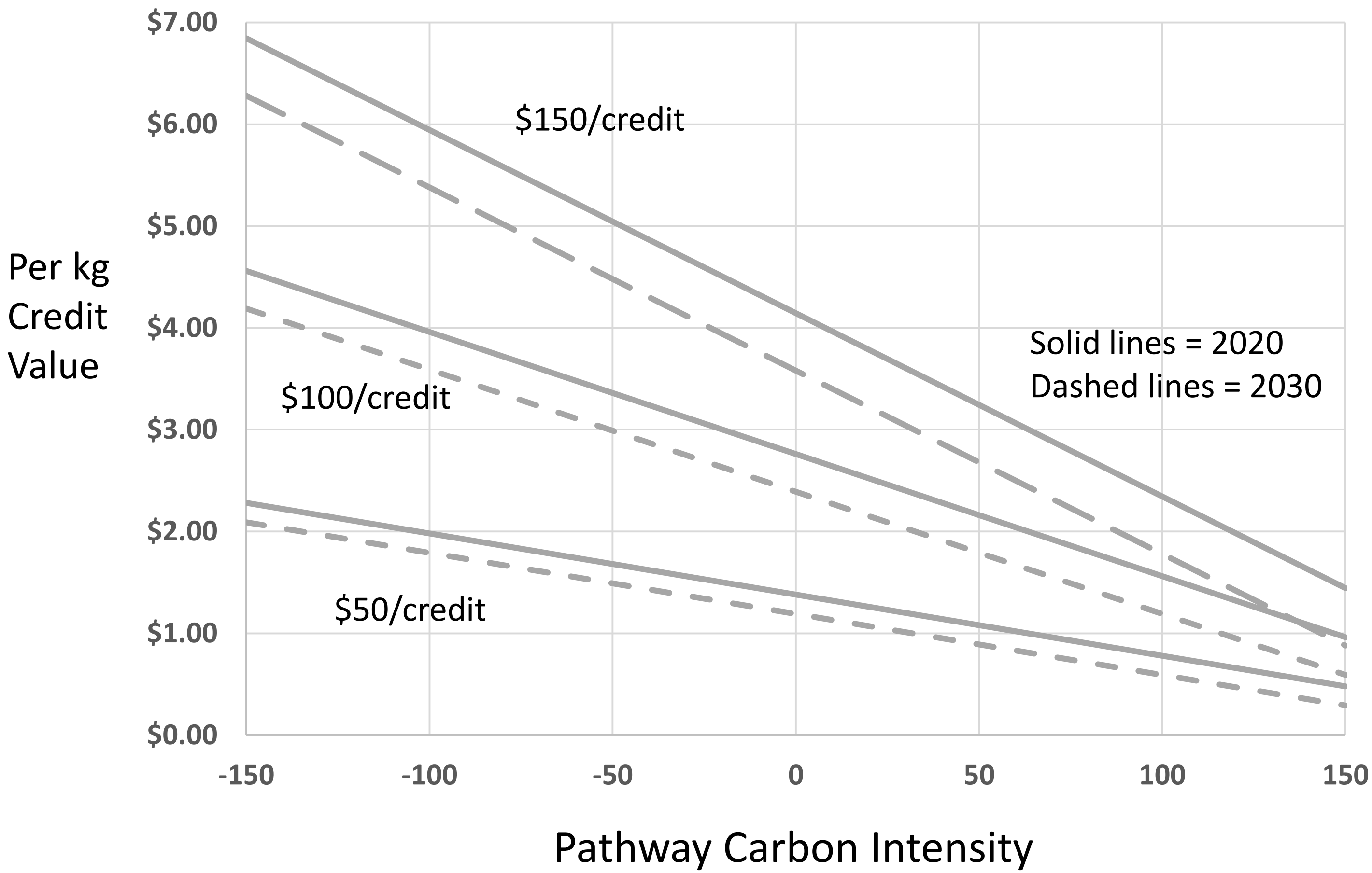
- **Renewable hydrogen pathways qualify for LCFS credits**
- **Organic pathways also qualify for RINS**
- **Credit prices are uncertain but recent prices have been robust and prices for LCFS credits are forecast to rise**





Interim Results

Depending on pathway CI, LCFS credit values can be substantial



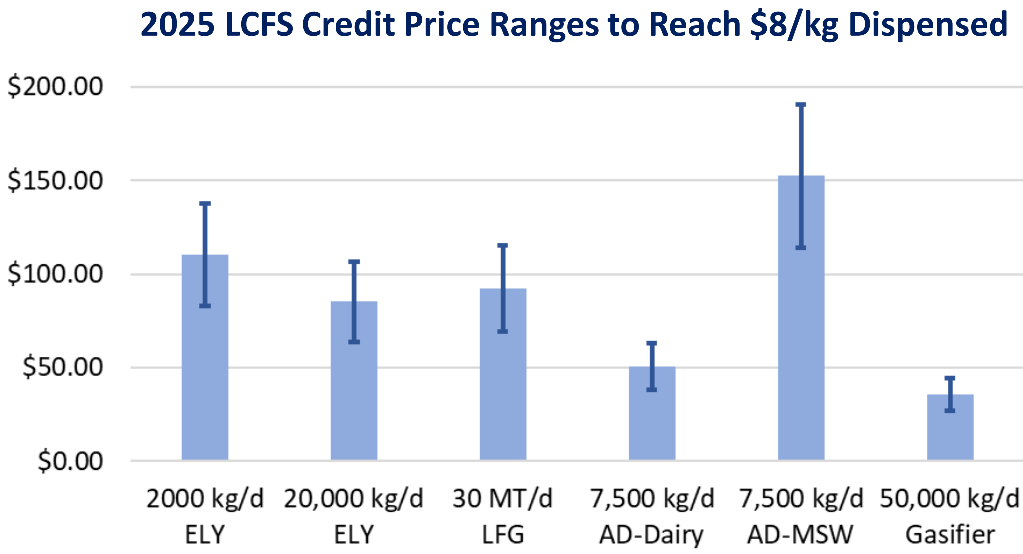
Interim Results

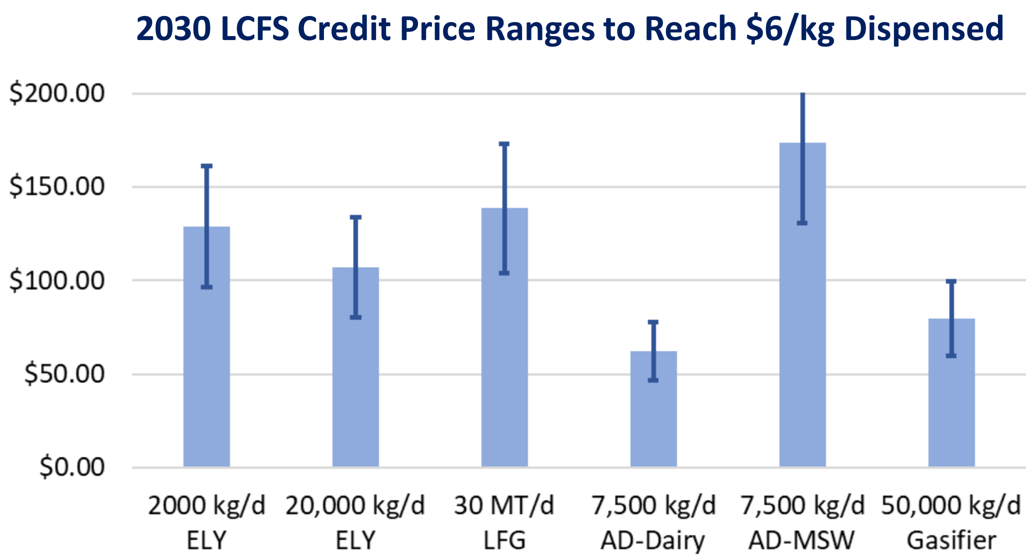
RH2 Pathway Carbon Intensities for Liquid Supply Chain

Preliminary

Pathway	Carbon Intensity 2025 g/MJ-CO_{2e}	Carbon Intensity 2030 g/MJ-CO_{2e}	Basis
Electrolyzer	35	25	• Lookup table adjusted for liquid supply chain with 20% in electricity CI in 2025 and 40% in 2030
Landfill Gas	110	95	• Lookup table adjusted for 20% improvement in electricity CI in 2025 and 40% in 2030
Dairy Biomethane	-320	-320	• Landfill case with fuel CI adjusted to CI of – 283 and improvements in electricity CI and SMR efficiency
MSW Biomethane	-10	-15	• Landfill case with fuel CI adjusted to -35
Gasification	85	70	• Landfill case with fuel CI adjusted to 5

Credit Prices Needed to Achieve Pump Price Benchmarks





Commentary:

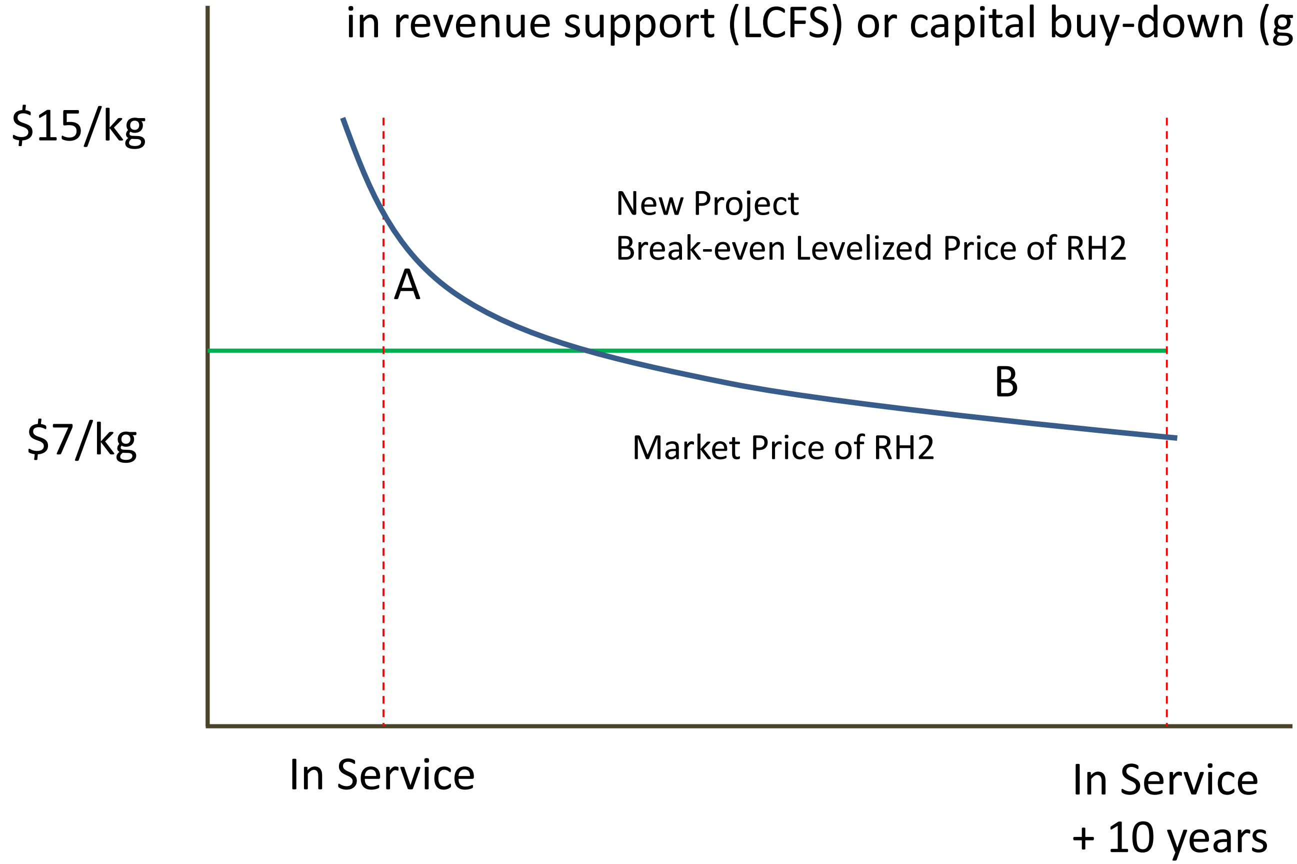
- **All pathways likely to be financially viable when tipping fees and environmental credits are considered**
- **Biomass recovery mandates likely to cause tipping fees to adjust to meet market price**
- **Over the long term, electrolytic hydrogen is likely to be the “price setter” for RH2 as biomass resource constraints come into play and eRH2 becomes the marginal supply**
- **Timing depends on policy on and access to out-of-state biomass**

Interim Results

“Rationale Investor” Analysis

Illustrative

Subsidy required to incent a rational investor is PV(B) – PV(A) in revenue support (LCFS) or capital buy-down (grant)



Policy and Program Issues

- LCFS credit prices can lead to a self-sustaining market but a mechanism to address price risk (such as has been proposed as part of the SB 1383) is needed to secure private debt financing
- Loan guarantees are another approach to achieve a similar impact
- The majority of likely pathways for biomass to renewable hydrogen do not have certified LCFS pathways
- Policy coordination is needed to avoid skewing the economic allocation of bio-derived fuels (RNG, RH2 and renewable liquid fuels)
- Local community concerns regarding biomass pathways need to be addressed (ensure job-creation and net local environmental benefits)
- Electrolyzer and liquefiers would benefit greatly from access to wholesale power markets – both direct cost impact and indirect via pathway carbon-intensity
- Lack of access to federal renewable fuel credits for e-fuel slants the playing field in favor of organics
- Support may be needed to foster entry of new technologies into the supply chain
- Additional support may be needed to ensure financial viability of connector stations and "early vintage" stations
- Further modeling analysis and program design will need to address the impacts of a mixed gas/liquid supply chain

Thank You. Questions and Comments?

#RH2@APEP

RENEWABLE HYDROGEN

UCI ADVANCED POWER AND ENERGY PROGRAM