| DOCKETED | |
|---|---|
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| **Project Title:** | Renewable Hydrogen Transportation Fuel Production |
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| **Document Title:** | Project Results Webinar Slides |
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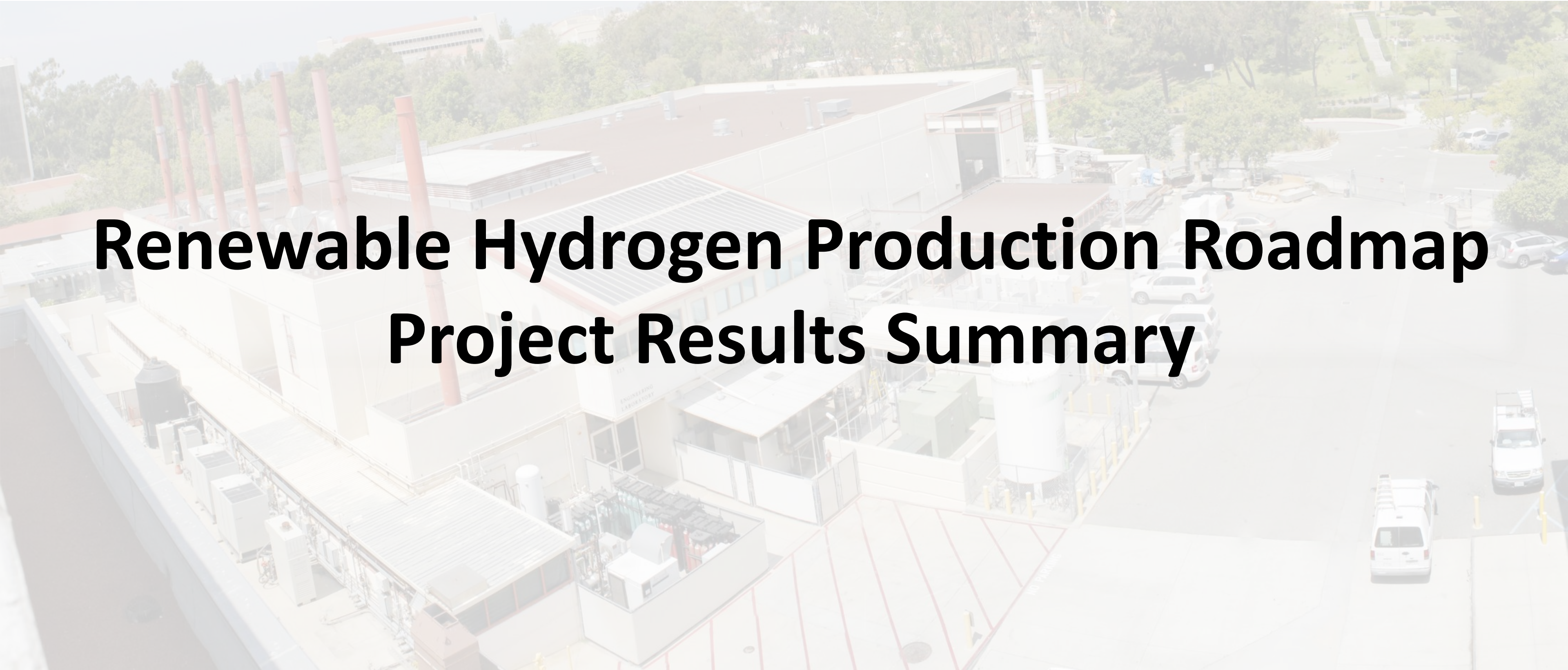
*Comment Received From: Jeffrey Reed*
*Submitted On: 8/28/2019*
*Docket Number: 17-HYD-01*

## Project Results Webinar Slides

*Additional submitted attachment is included below.*



# Renewable Hydrogen Production Roadmap Project Results Summary

ADVANCED POWER & ENERGY PROGRAM
UNIVERSITY of CALIFORNIA • IRVINE


Dr. Jeffrey Reed
Professor Scott Samuelsen


August 28, 2019

# Acknowledgements

FUNDING PROVIDED BY THE CALIFORNIA ENERGY COMMISSION

STATE OF CALIFORNIA ENERGY COMMISSION SINCE 1975

- 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 through interviews and comments to the docket

# 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 assessed the full production and delivery chain build out and cost over time
  - Quantitative
  - Time-phased
  - Focused on requirements to serve the evolving LDV population in the context of additional sources of demand for renewable hydrogen
  - Assessed conditions needed for the sector to become self-sustaining

- Goal was to make visible key aspects of the renewable hydrogen production through delivery chain:
  - Understand the current cost and performance of the supply chain
  - Capture positive and negative learnings from early projects to guide process and policy improvements and build data on current technology costs
  - Provide a fact base to support investment analysis by value chain participants and program development by state agencies

# Agenda – Renewable Hydrogen Production Roadmap Review

- Overview and Summary
- Renewable Hydrogen Dispensed Cost Analysis
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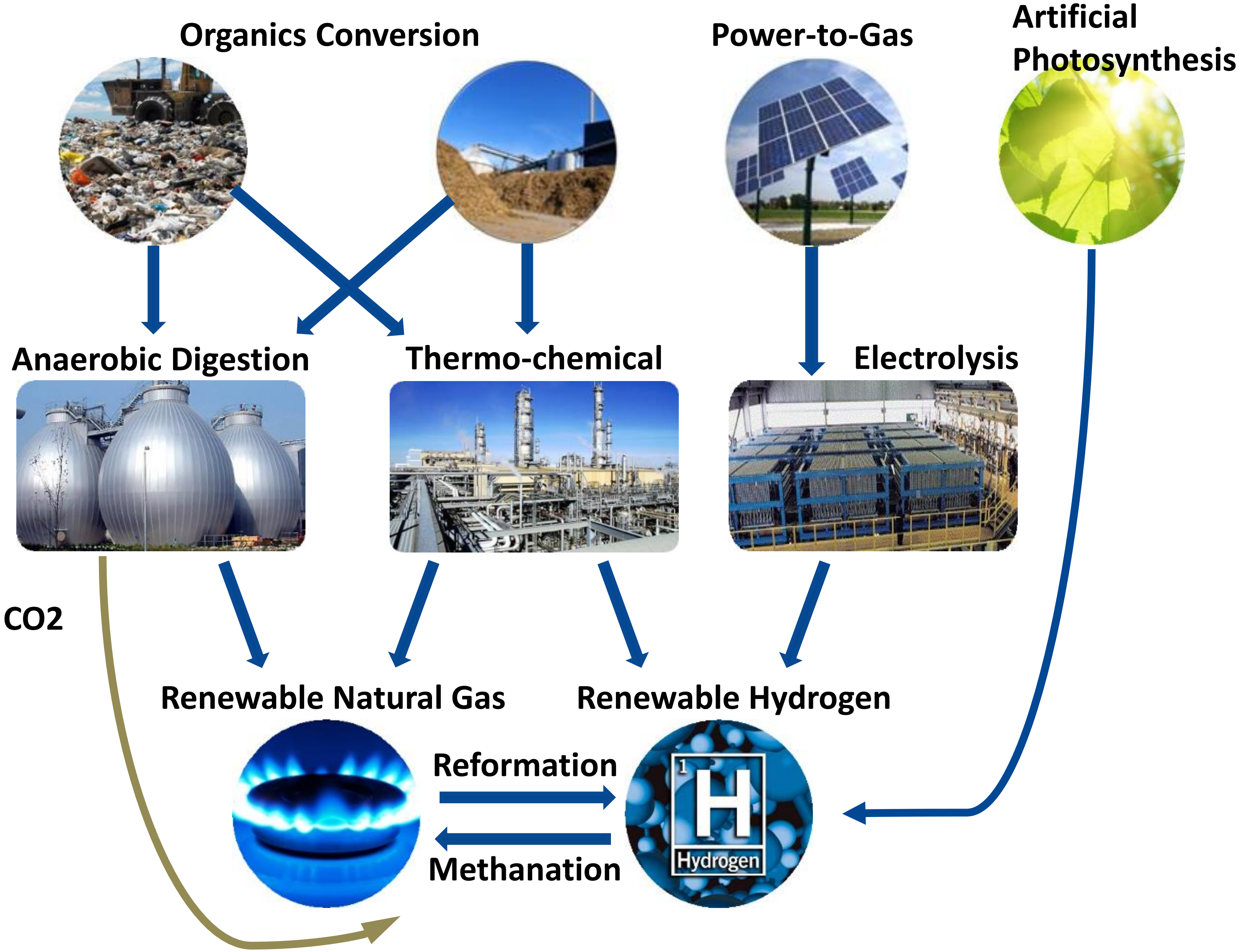
# Renewable and Zero-carbon Gaseous Fuel Pathways



# Renewable Hydrogen Roadmap for California

### Technology Characterization (Cost and Performance)

- Electrolysis, AD, gasification
- Developer input, literature, learning-curve analysis

### Feedstock Cost and Availability

- DOE billion ton report primary source for organics
- Lazard wind and solar forecast

### Plant-Gate-to-Dispenser Cost Evolution

- DOE HDSAM 3.0 model
- Station size and utilization from ARB CHIT analysis
- Learning curve cost forecast

### Dispensed Cost of Renewable Hydrogen Evolution

- All-in unsubsidized cost by production and delivery pathway
- Impact of environmental credits and secondary revenue (tipping fees)

### Renewable Hydrogen Demand Evolution

- Industry and developer input
- State agency reports (e.g. Mobile Source Strategy)
- DOE H2@Scale and lab reports

### Candidate Site Identification

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

### Integrated Renewable Hydrogen Roadmap

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

### Stakeholder Engagement

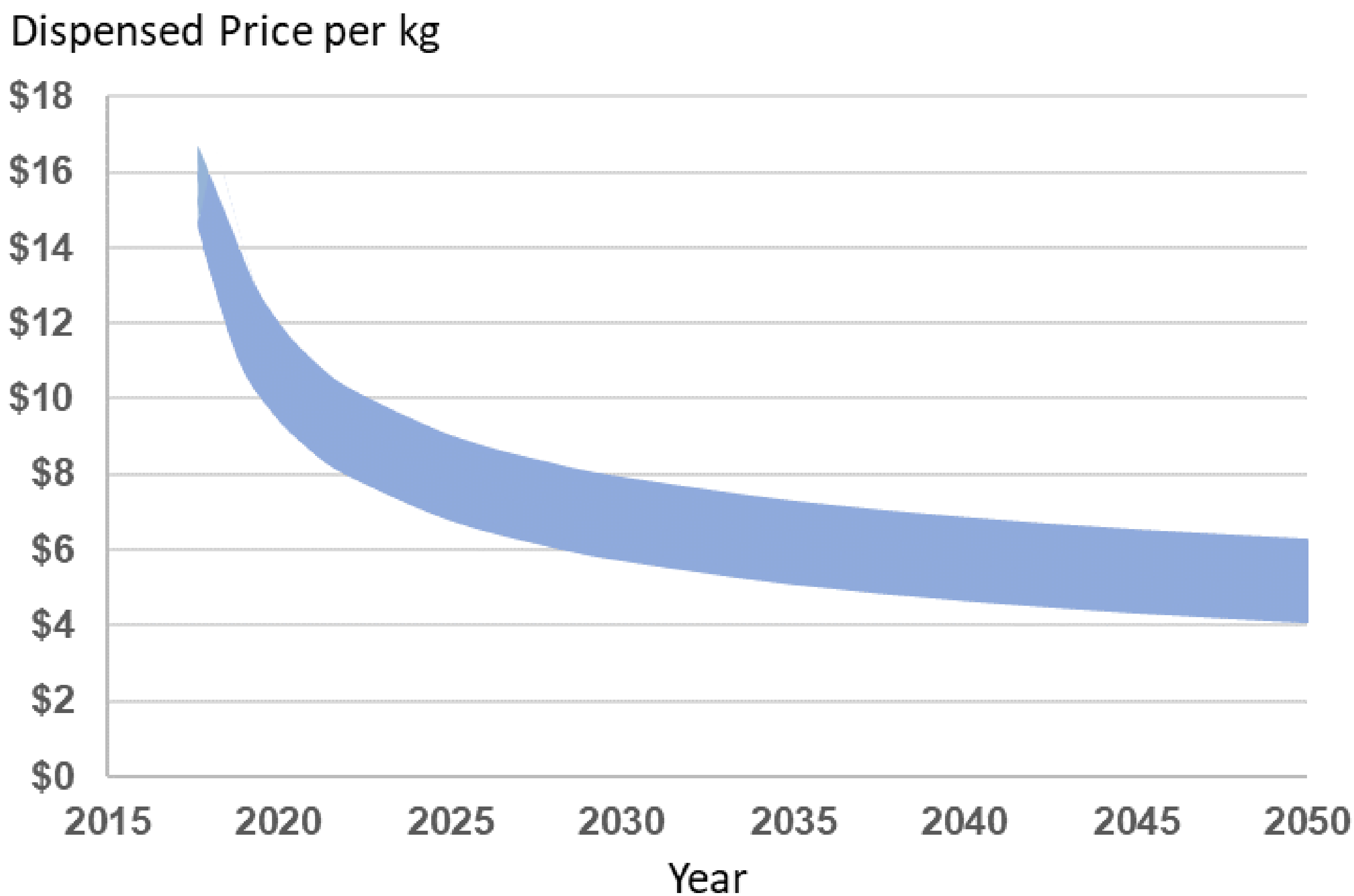
# Key Findings

- RH2 demand could reach over 400 million kg/yr by 2030 and 4,200 million kg/yr by 2050 (equivalent to 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 toward larger station sizes and greater use of liquid transport and storage for next generation stations and beyond

# Key Findings

- 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
    - Electrolytic hydrogen will be needed to meet demand over the long term
    - Electrolyzer and thermochemical systems need commercialization support
- A self-sustaining hydrogen transportation sector appears to be possible by the mid to late 2020's assuming progress on cost reduction meets base-case projections and LCFS credit prices remain above ~$100/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

# Potential Hydrogen Pump Price Evolution



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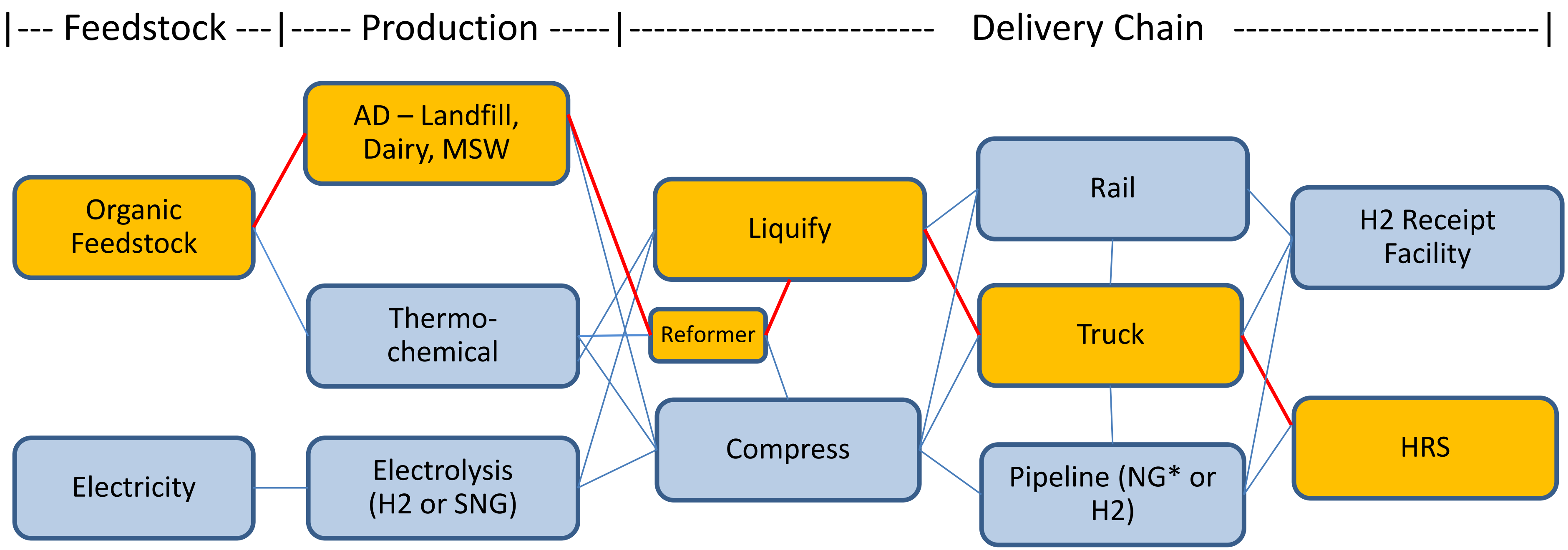
# RH2 Delivered Cost Analysis




## Cost Modeling

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

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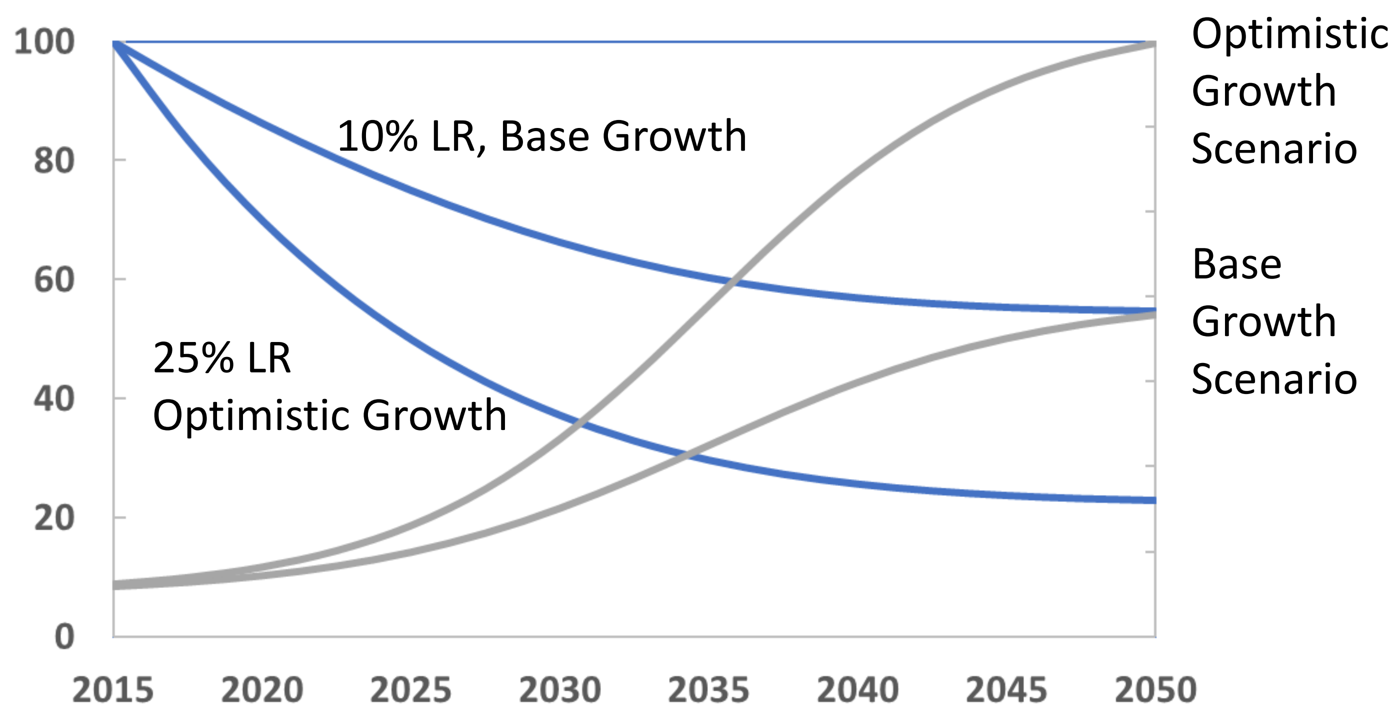
# Technology Forecasting Methodology

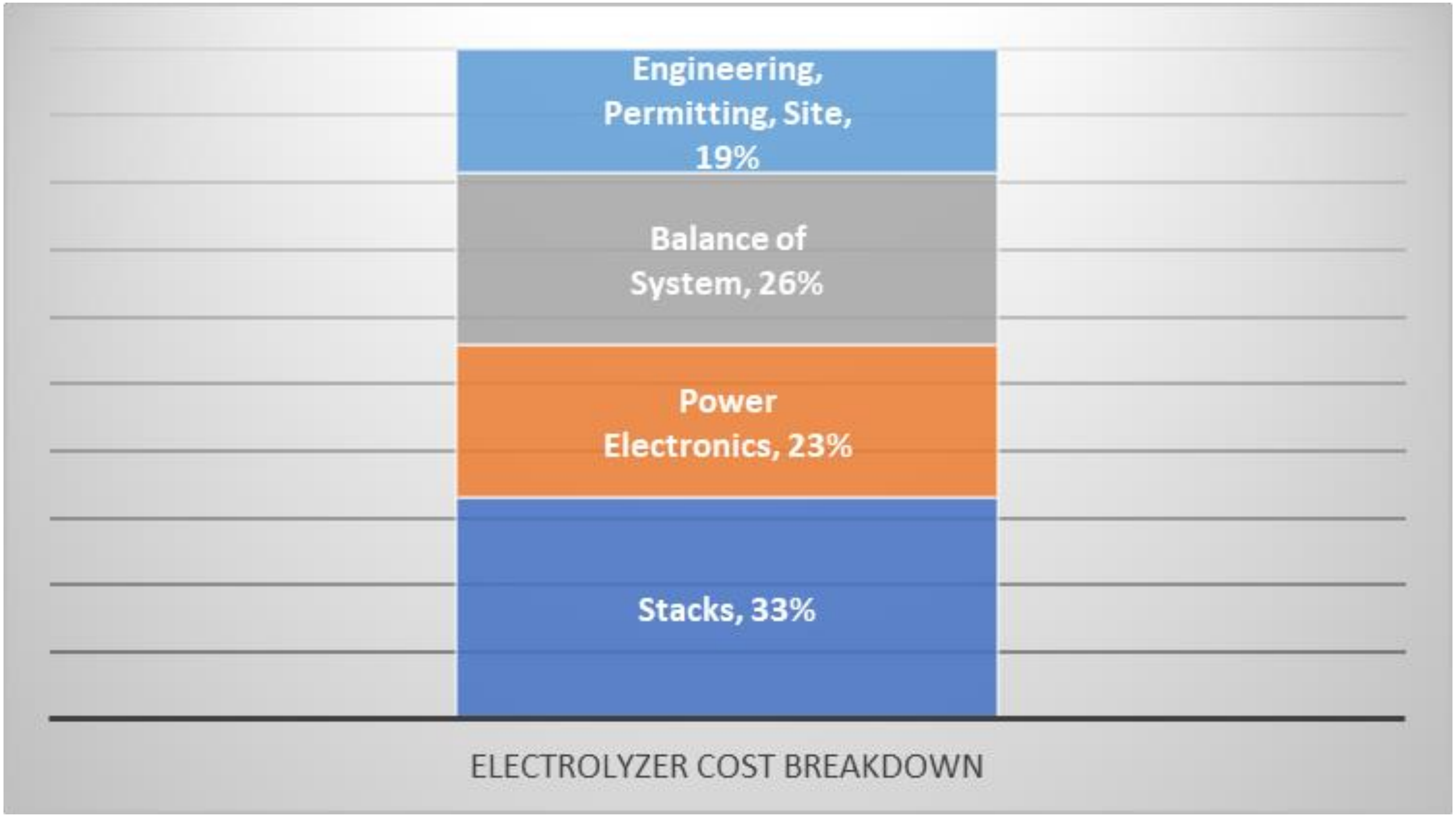
- Technology forecasting methods
  - Expert elicitation (researchers, equipment vendors)
  - Progress or learning rate analysis / trend analysis
  - Bottom-up analyzes based on design, bill-of-materials and production scale
  - Analogy or proxy analysis
- Source materials and team analysis employed all these methods in this study
- Dollars normalized to $2018 using Consumer Price Index and/or Chemical Engineering Plant Cost Index (CEPCI)
- Cost data and projections adjusted for currency, time point, scope of supply and project size
- Order of +/- 25% uncertainty remains after adjustment to common basis

# Market Growth and Learning Rate

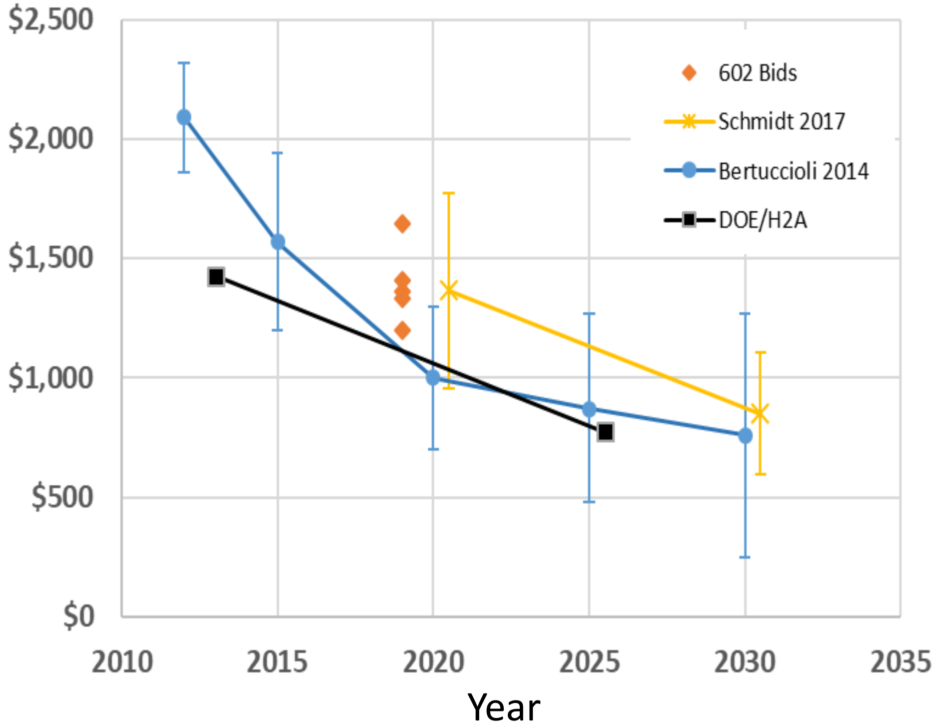


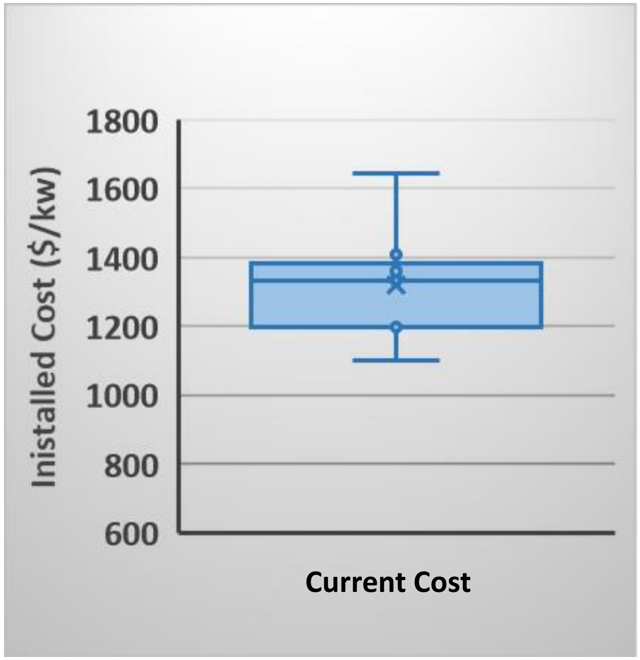

- **Progress or learning rate has proven to be an accurate predictor of cost reduction for many technologies**
- **This method forecasts a percent reduction in cost over time or as a function of cumulative production of a technology with cumulative production showing the better correlation ("Wright's Law")**
- **Learning rates (cost reduction per doubling of cumulative production) of 5% to 20% are typical with higher rates more common for digital and electrochemical technologies**

# Typical Electrolyzer Total Project Cost Breakdown

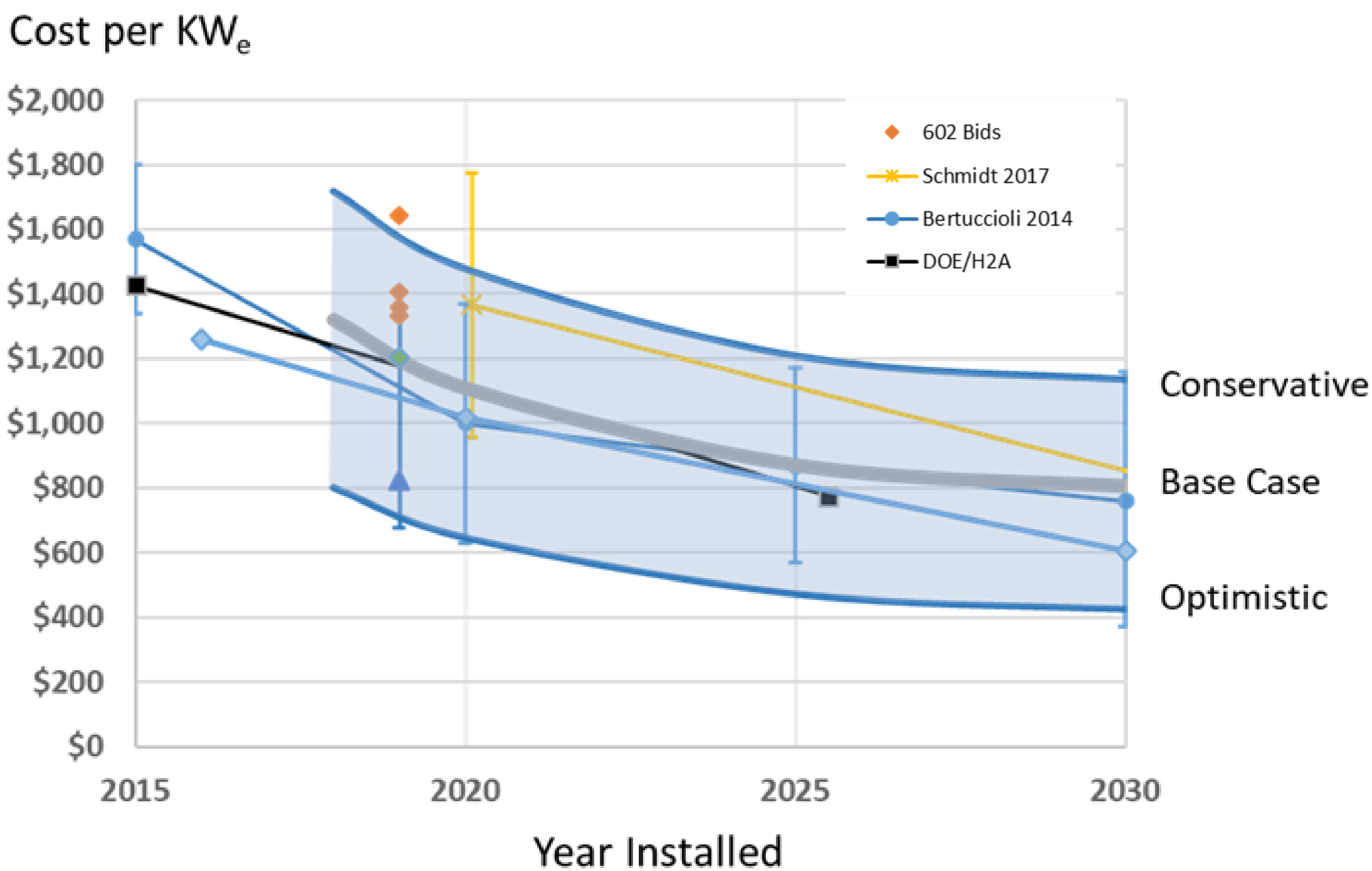


# PEM Electrolyzer Cost

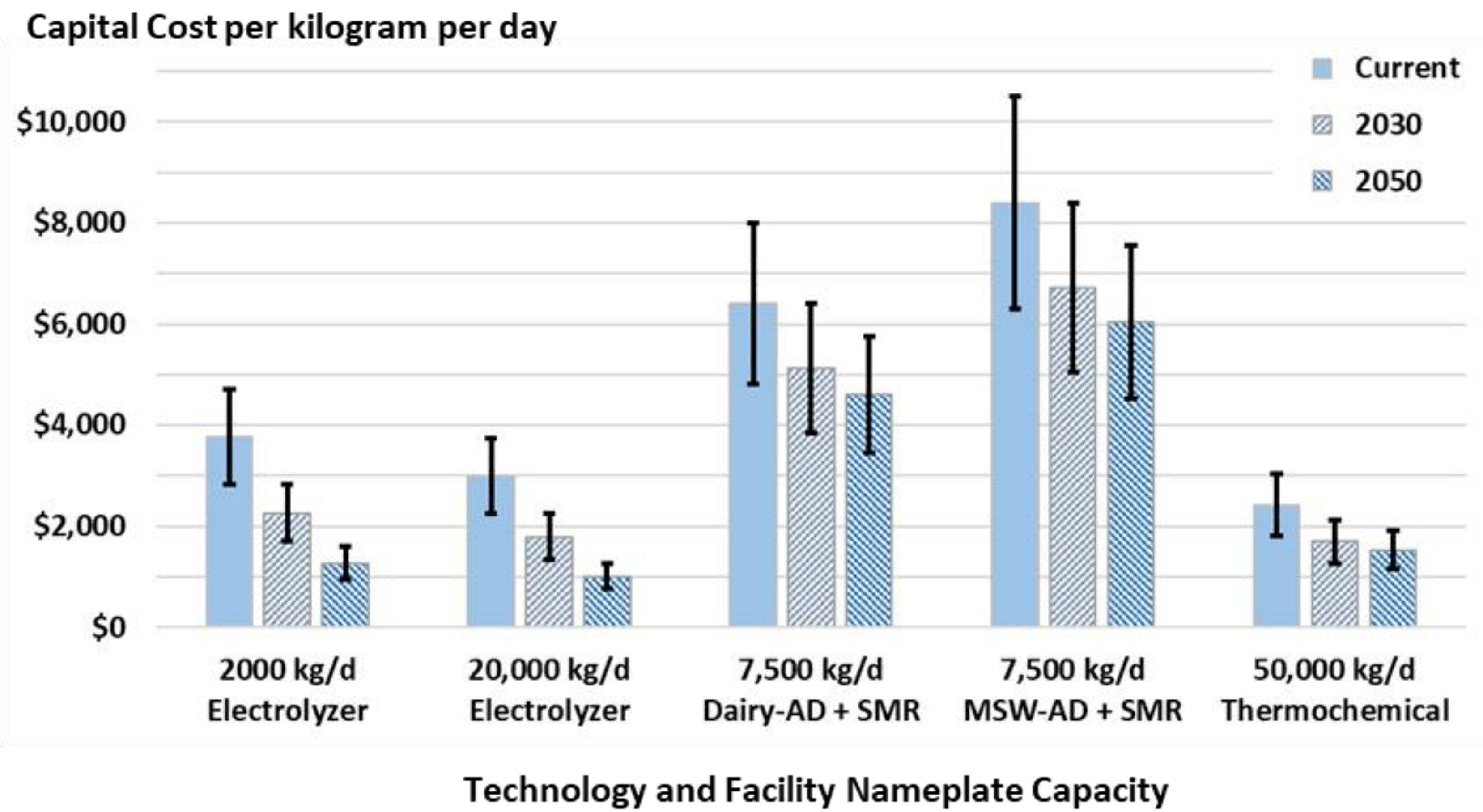


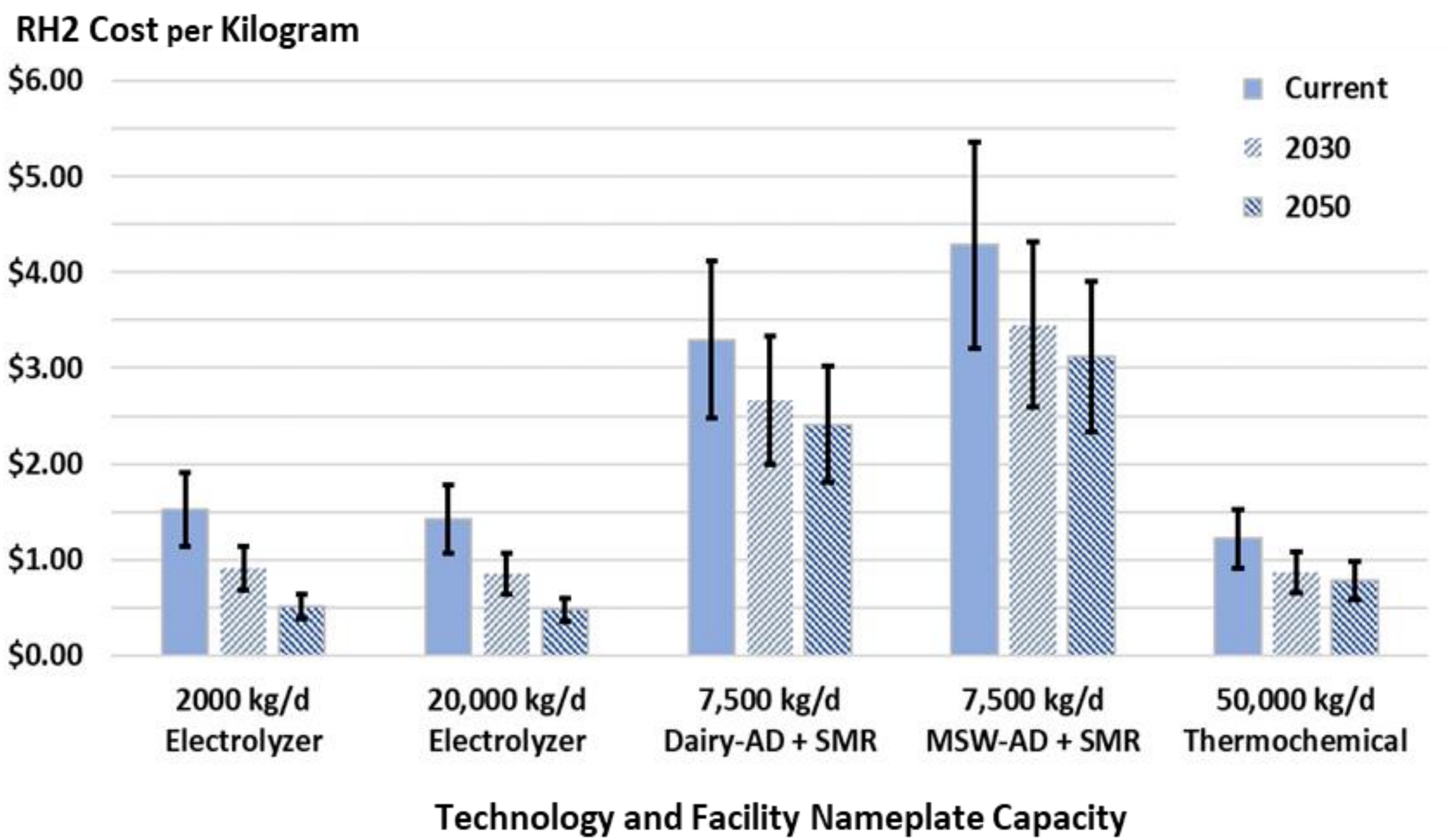
# Electrolyzer Cost Forecast



# Capital Cost Evolution



# Conversion Cost Progression



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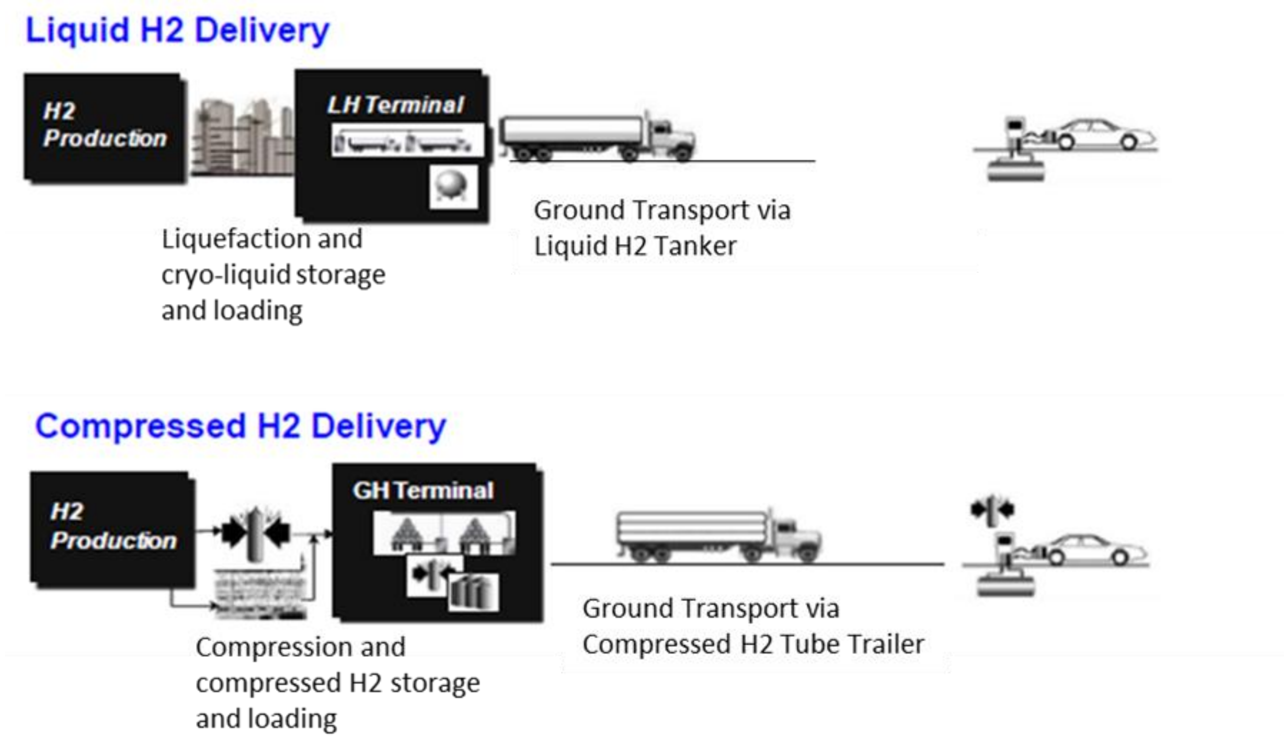
# Plant-Gate-to-Dispenser

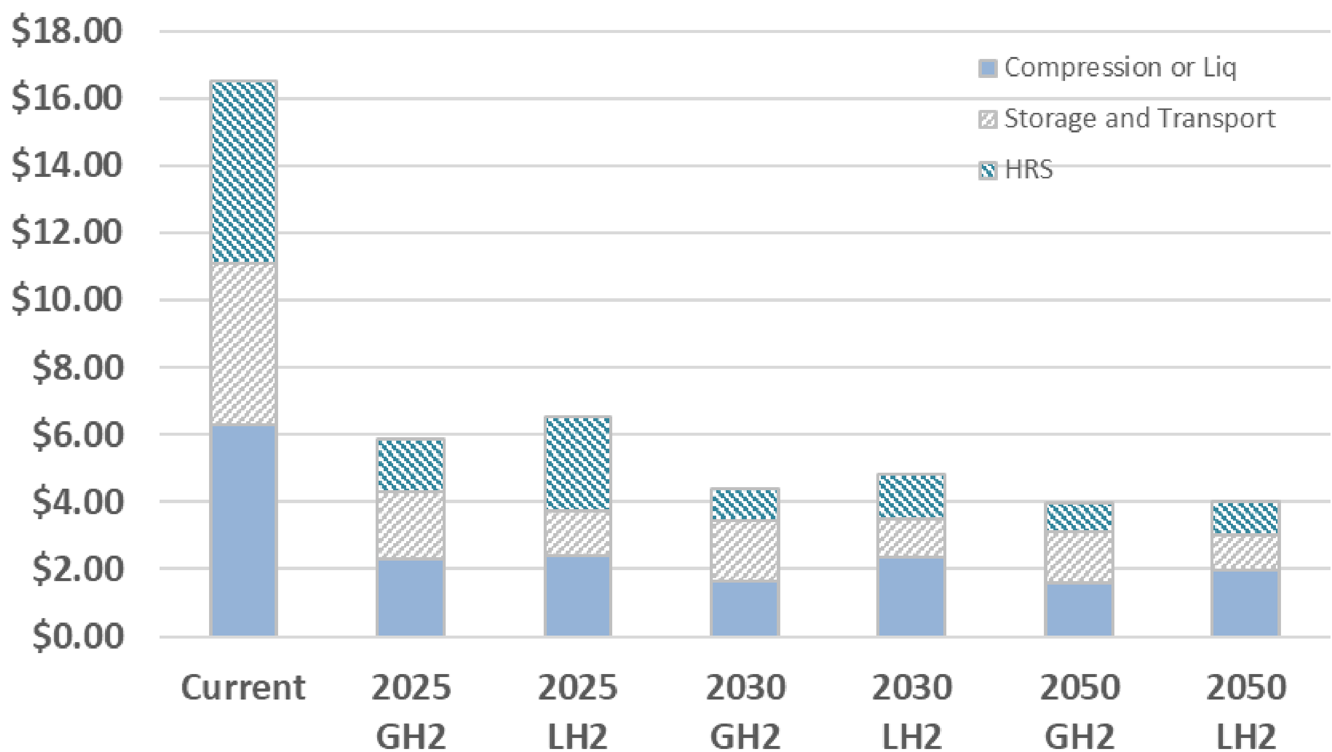
- **Two approaches in use in California – likely to continue to have a "two-mode" delivery and station network so supply-chain integration is a consideration**




Source: UCI APEP adapted from DOE H2A Delivery Scenario Analysis Model Version 3.0 (HDSAM 3.0) User's Manual

- **Natural gas system will play a role transporting biomethane and RH2 blends**
- **Future evolution may include at-station production via electrolysis or reformation and new transport and storage media such as hydrogen-carrying liquids**

# Cost Progression for Hydrogen Supply Chain




**Input Assumptions**

| | Current | 2025 | 2030 | 2050 |
|---|---|---|---|---|
| **Station Size Kg/d** | 300 | 600 | 1200 | 1500 |
| **Utilization** | 40% | 70% | 80% | 80% |
| **Production Volume** | Low | Medium | High | High |

Source: UCI APEP using HDSAM 3.1

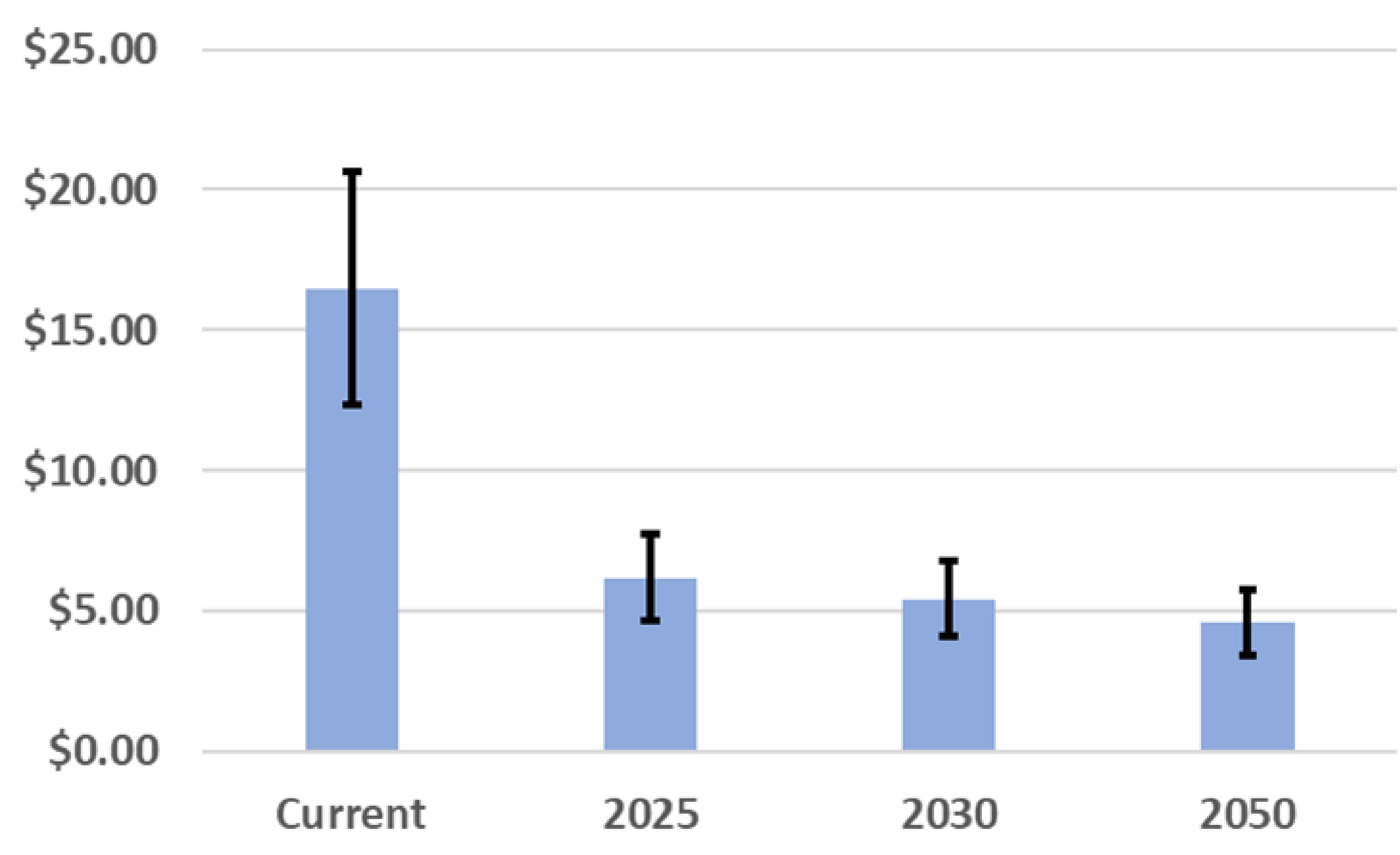
# Potential of Forecourt Production

- **Constraints to deployment of forecourt solutions**
  - **Electrolyzer face low scale penalty but need access to low-cost renewable grid electricity so transmission level connection and real-time rates or direct access will be a pre-condition to significant deployment where grid energy is needed**
  - **Reformer systems are scale sensitive and produce NOx emissions so technology advances are needed, and siting may be limited in non-attainment areas**
  - **The need for additional space at the station may also limit this approach to MD/HD size stations and locations in less dense areas**

- **Forecourt RH2 production could have a net benefit of ~10 - 15% on dispensed cost if the above constraints are addressed**

- **Timing is also a consideration**
  - **Aggressive station build to reach 1000 stations by 2030 may outpace the evolution of forecourt solutions and either limit deployment or require retrofit approaches**
  - **If cost advantage is substantial, forecourt stations may be added into the network to compete with truck-supplied stations**

# Cost Progression for Hydrogen Supply Chain



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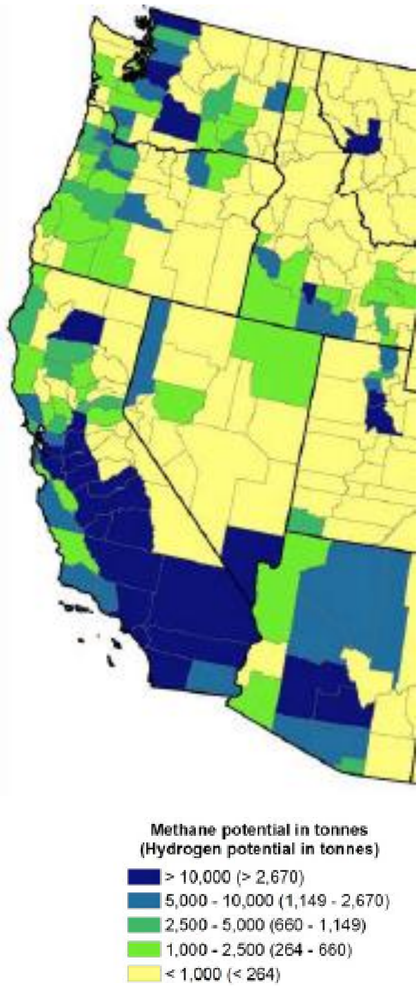
# Feedstock Cost and Supply Analysis

- **Biomass feedstock**
  - DOE Billion Tons Report was the primary source (estimates quantities as a function of roadside cost)
  - Manure biomethane from ARB Short Lived Climate Pollutant Strategy
  - Landfill resource potential from Jaffe et al.
  - 2017 IEPR as supplemental reference
- **Renewable electricity for electrolysis**
  - Solar and wind are the assumed resources
  - Lazard LCOE version 12.0 and CPUC RESOLVE resource definition were the primary sources
  - Co-location of electrolyzers and renewable resources assumed as cost-minimizing option

# Organic Feedstock Supply

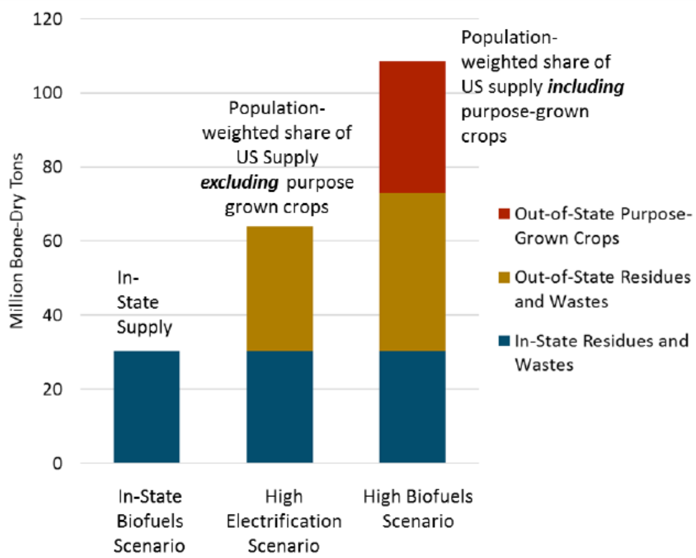


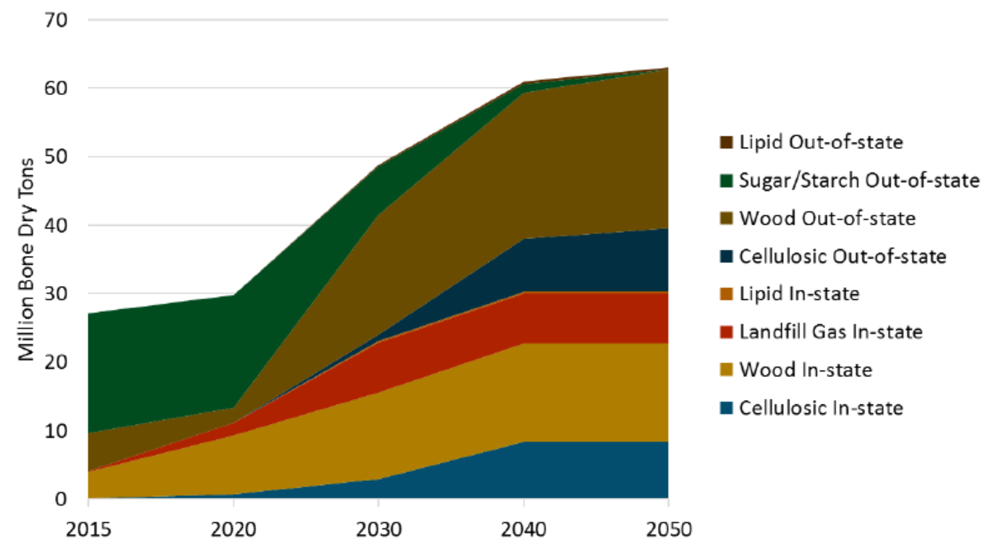

Map Source: NREL

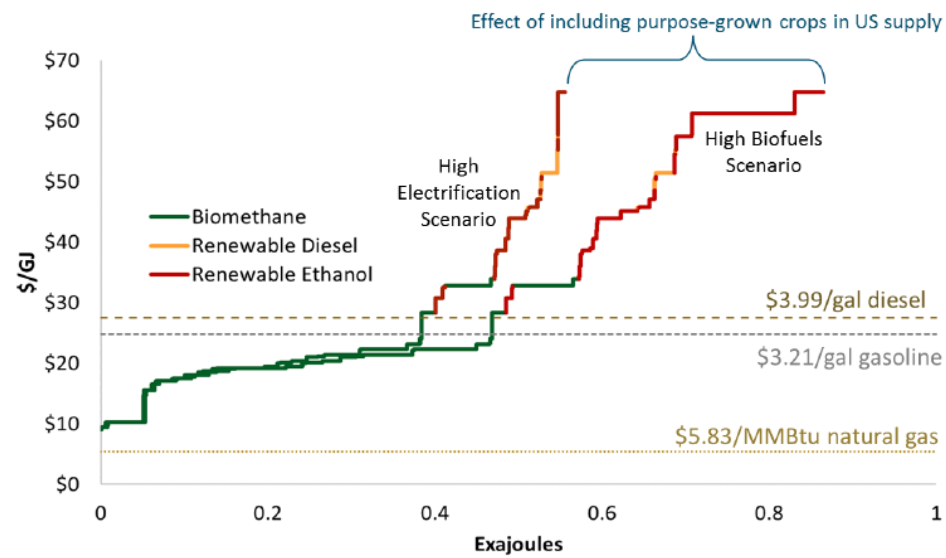
| Feedstock | Conversion | 2030 Quantity (million dry tons / PJ per yr.) | | |
|---|---|---|---|---|
| | | $30/ton | $60/ton | $100/ton |
| **Forest, Agricultural Residue, Woody MSW** | Thermochemical | 12.5 / 227 | 37.6 / 686 | 63.0 / 1160 |
| **Energy Crops** | Thermochemical | 0 | 0 | 0.563 / 10.6 |
| **High-moisture Organic MSW** | Anaerobic Digestion | 0 | 0.977 / 17.7 | 1.97 / 35.7 |
| **Total Annual Supply** | -- | 12.5 / 227 | 38.6 / 704 | 65.5 / 1200 |

| Feedstock | Source | 2030 Quantity (PJ biomethane per yr.) |
|---|---|---|
| **Dairy Manure** | (CA_Air_Resources_Board 2016) | 12 (10^6 milking cows) |
| **CA Landfill Gas** | (Jaffe, Dominguez-faus, and Parker 2016) | 43 |

# Potential Impact of Out-of-State Supply -- E3 Deep Decarbonization Study (2018)



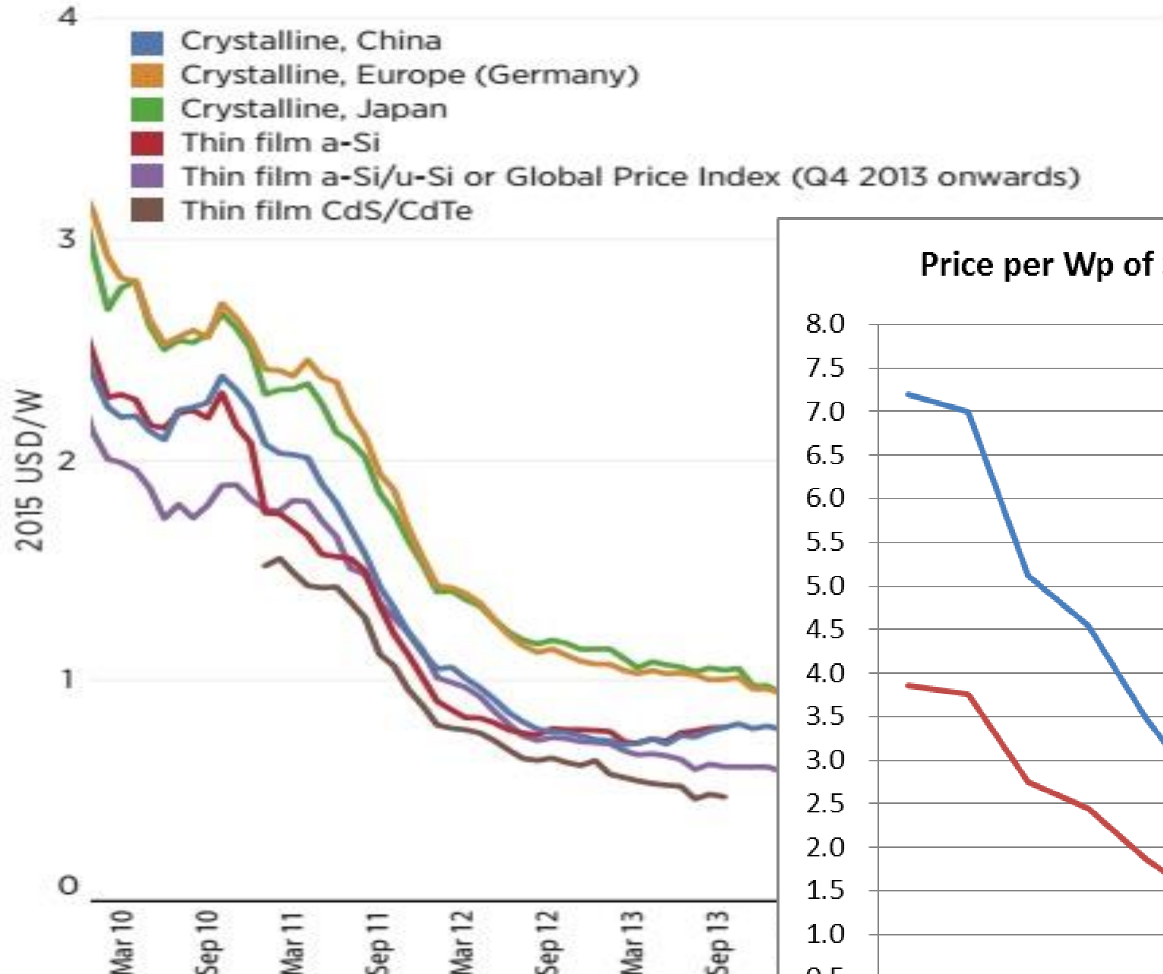



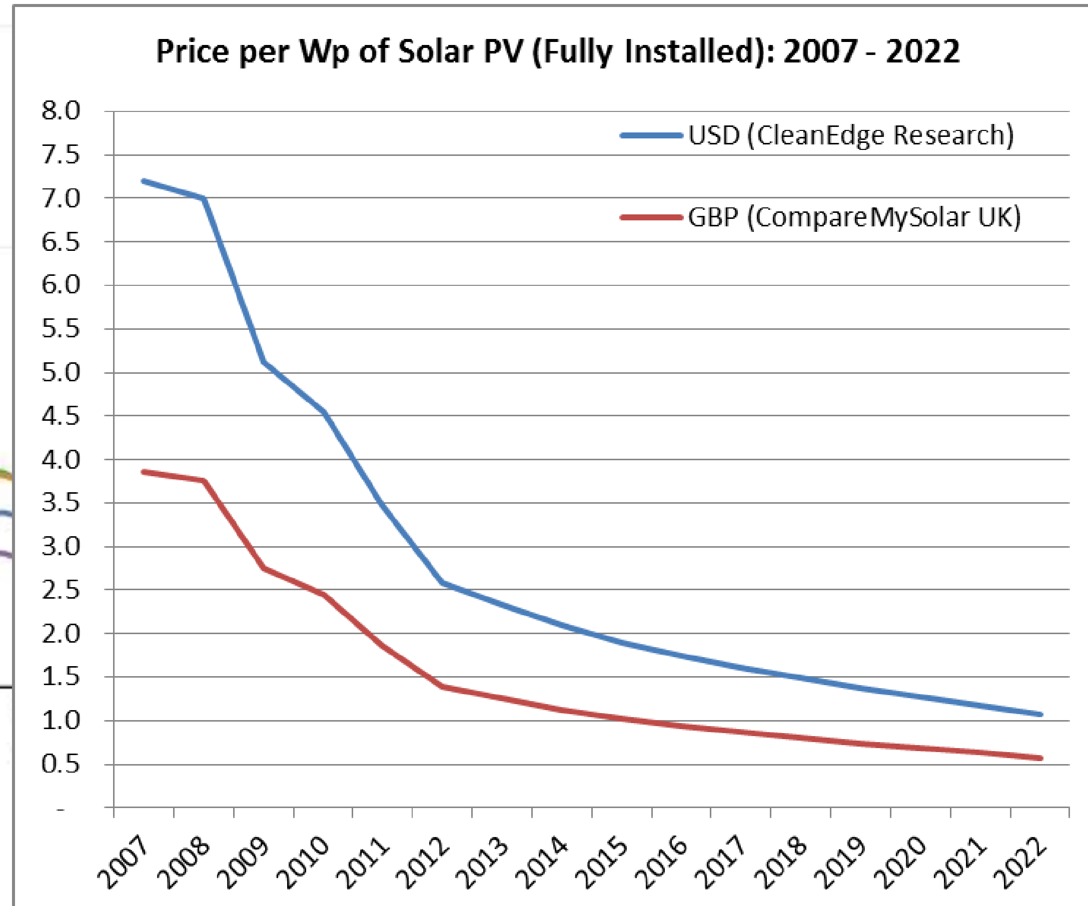




0.4 Exajoules equivalent to
2.7 billion kg RH2 at 75% SMR efficiency

Source: Graphics from E3 Deep Decarbonization Report

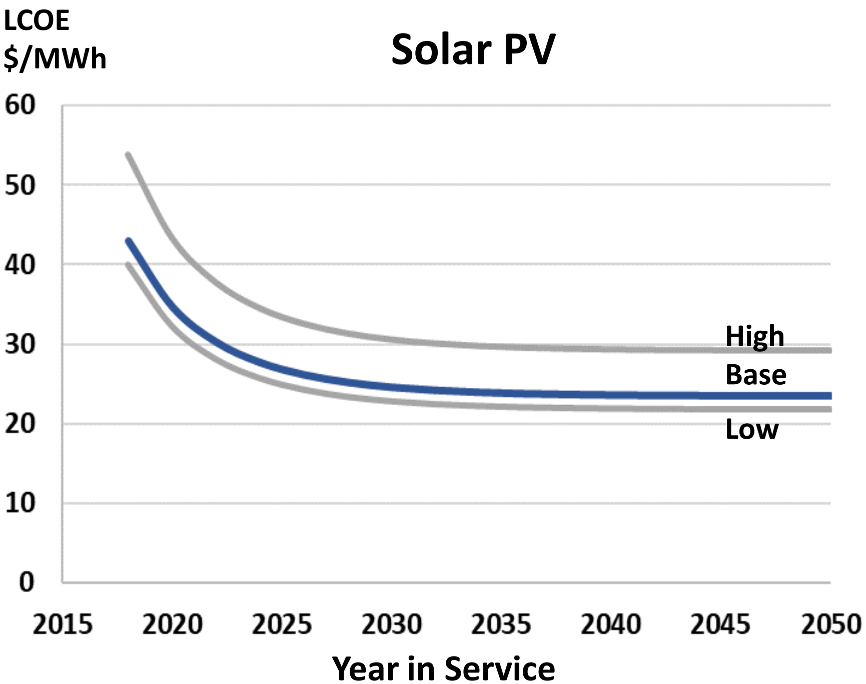
# Renewable Power – Feedstock for Electrolytic Hydrogen

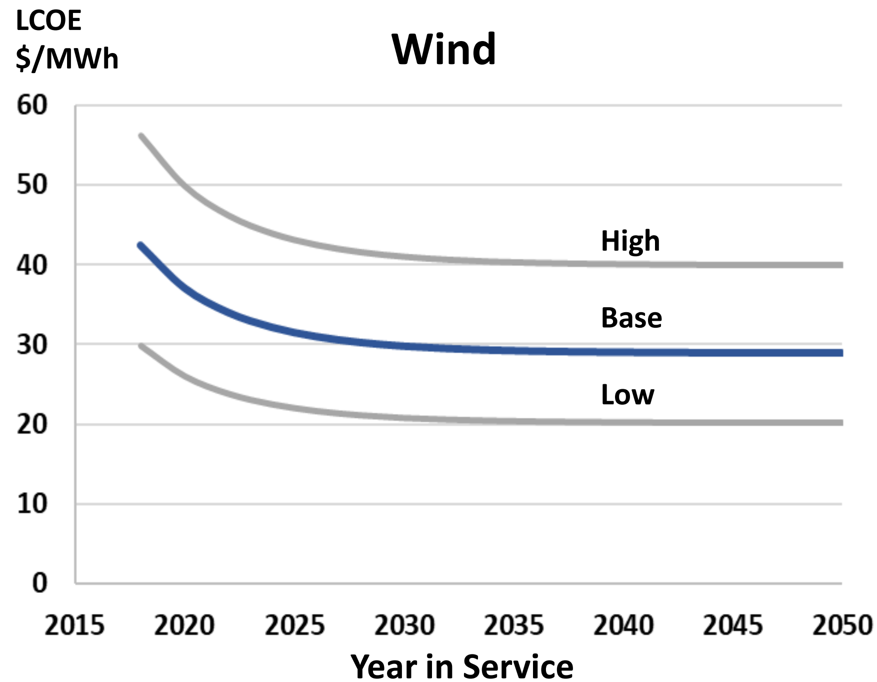



www.newenergyupdate.com, 2017

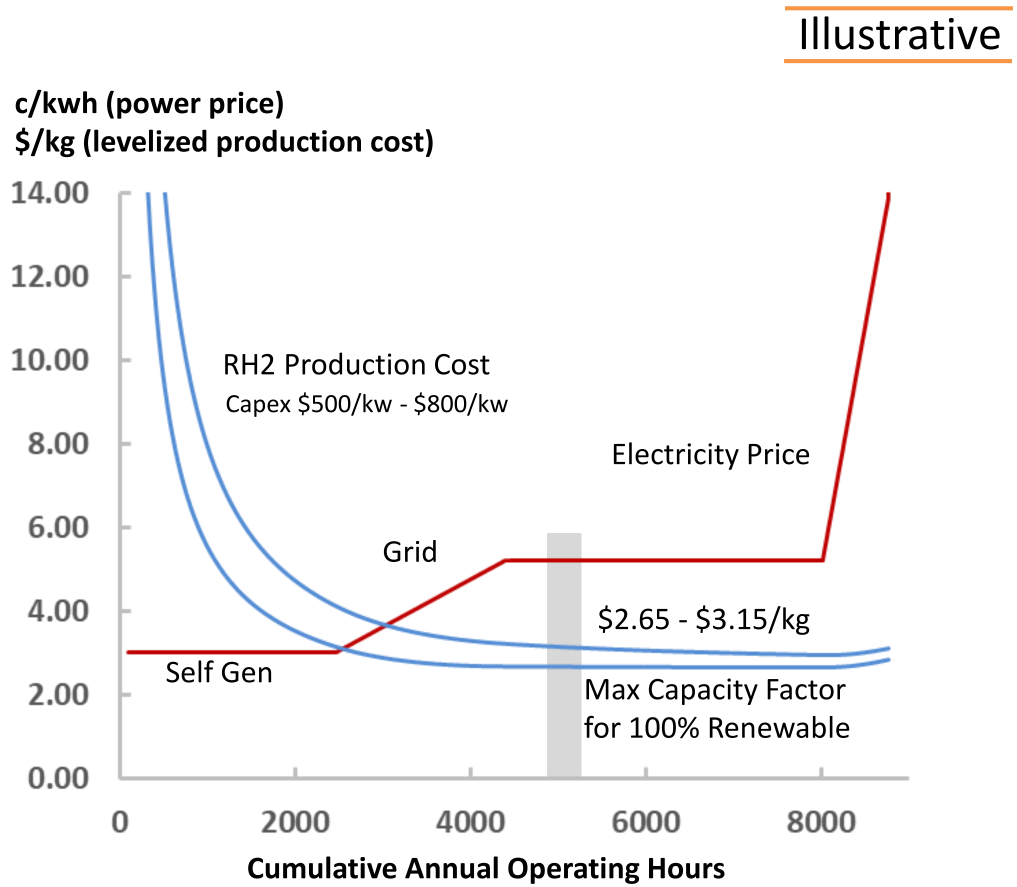
# Solar and Wind New-build Self-generation Costs



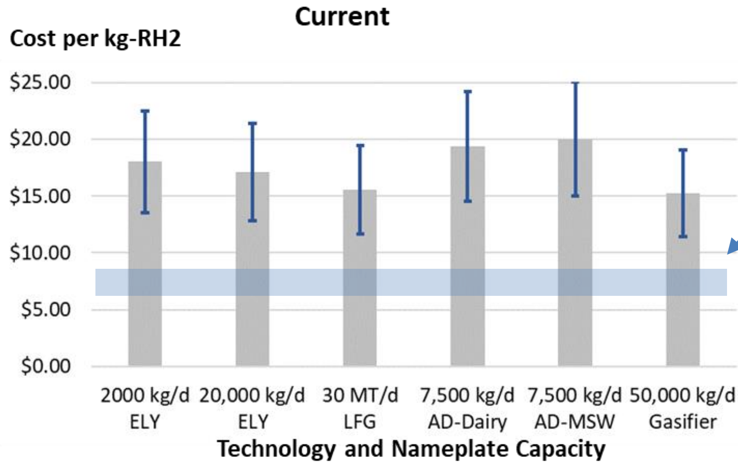

- Low and mid cases based on Lazard's Levelized Cost of Energy, Version 12.0
- High based on CPUC RESOLVE model wind and solar cost assumptions

# Electrolytic Hydrogen Production Cost in 2030 Timeframe



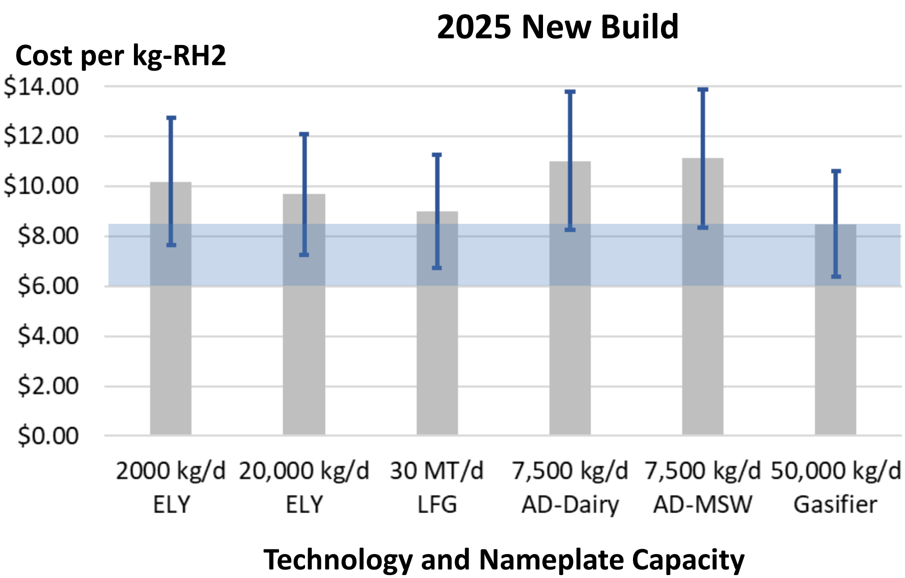

- **Representative case of self-generated solar augmented with wind PPA or spot purchases**

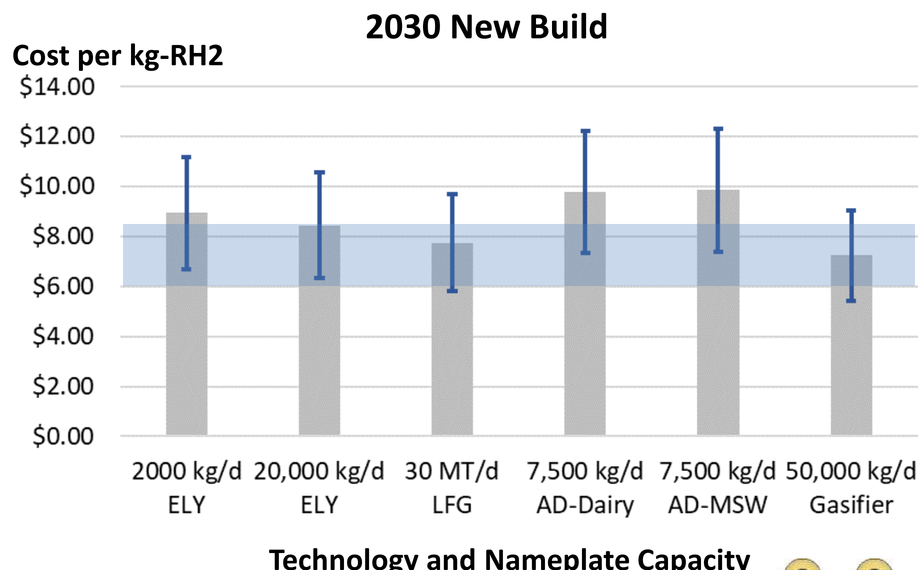
# Full Dispensed Cost of RH2 without Credits




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



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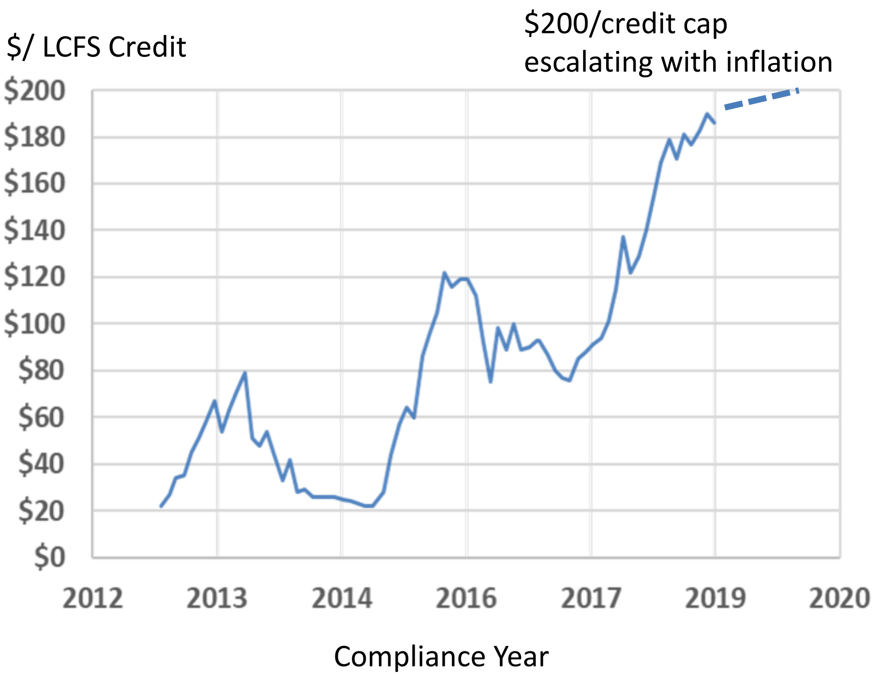
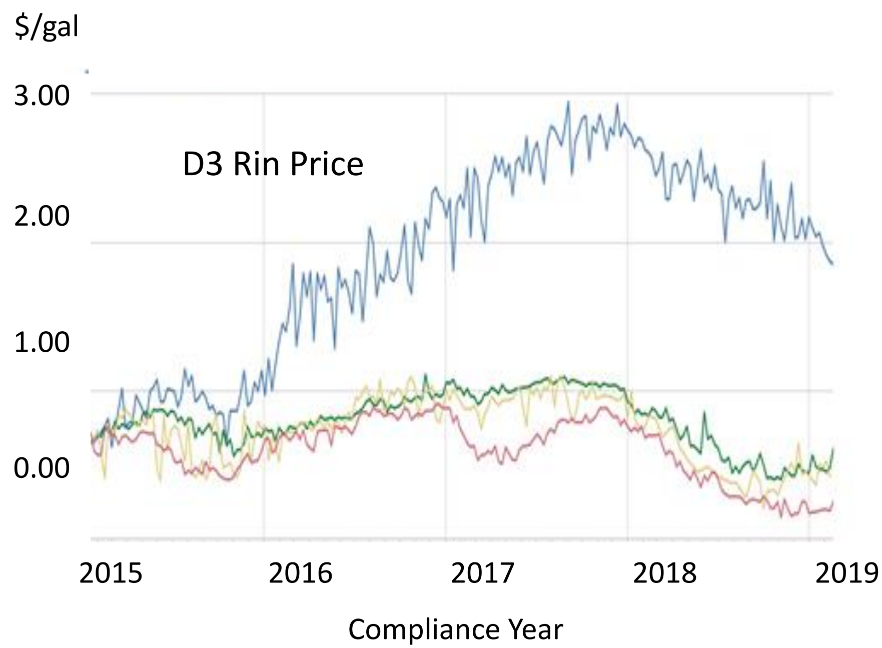
# Role of Credits

- Renewable hydrogen pathways qualify for LCFS credits
- Organic pathways may also qualify for RINS (pathway applications bending at EPA)
- Credit prices are uncertain but recent prices have been robust and prices for LCFS credits are forecast to rise



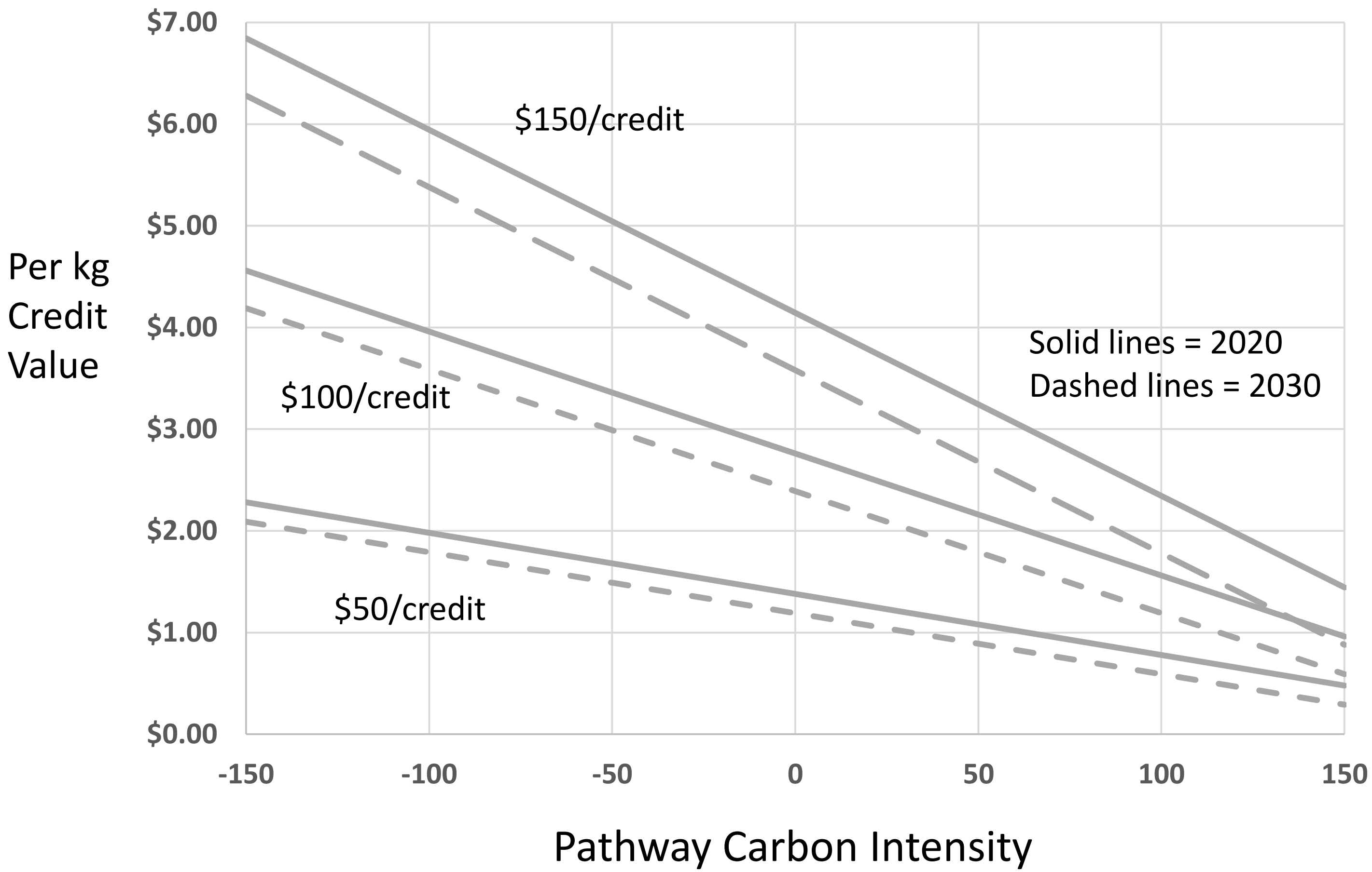



# RH2 Pathway Carbon Intensities for Liquid Supply Chain

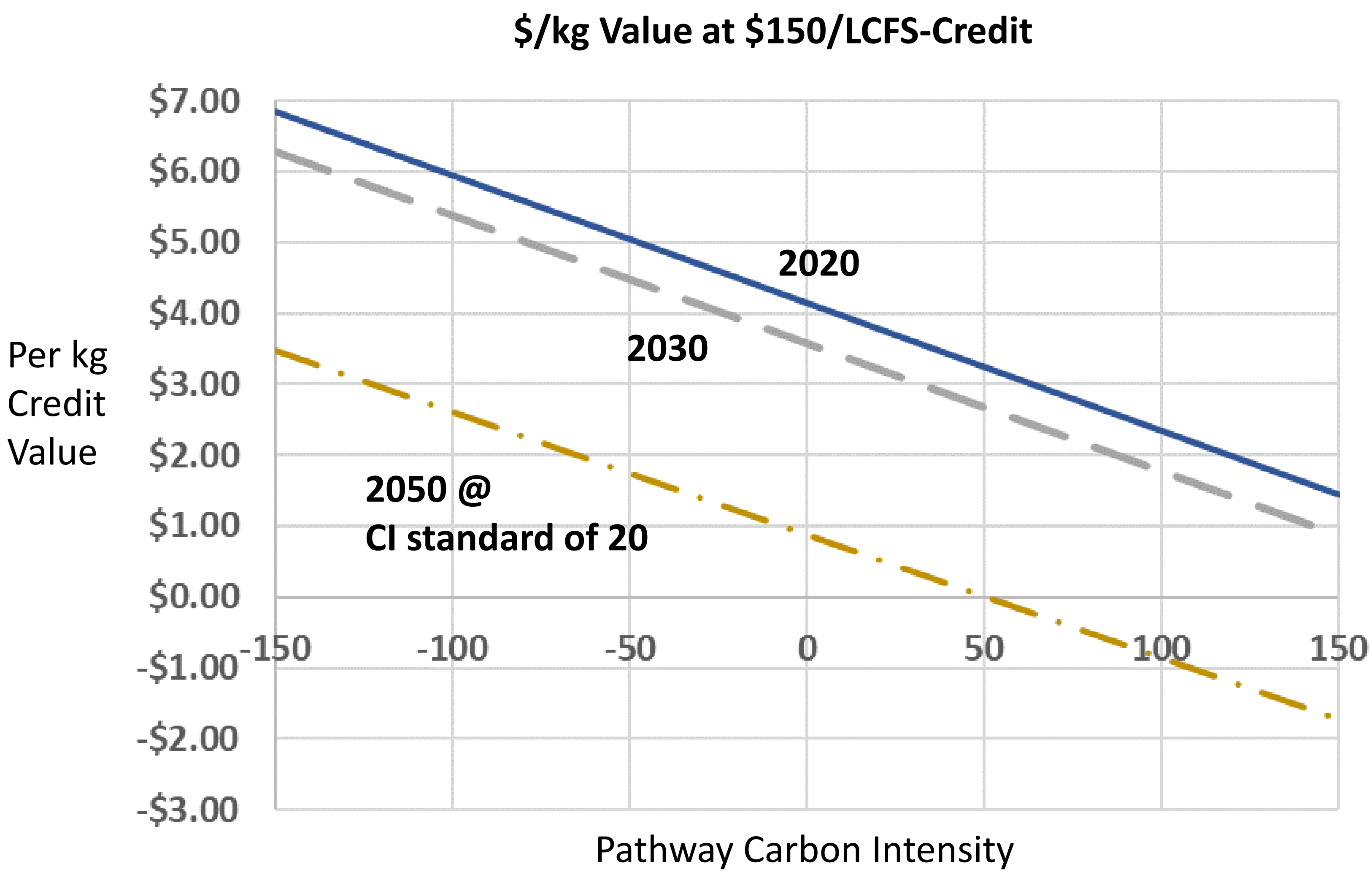
| Pathway | Carbon Intensity 2025 g/MJ-$CO_{2e}$ | Carbon Intensity 2030 g/MJ-$CO_{2e}$ | Basis |
|---|---|---|---|
| Electrolyzer | 35 | 25 | • Lookup table adjusted for liquid supply chain with 20% improvement in electricity CI in 2025 and 40% in 2030 |
| Landfill Gas | 110 | 95 | • Lookup table adjusted 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 |

Source: UCI APEP based on ARB CI look-up table and pathway CI reports

# Depending on pathway CI, LCFS credit values can be substantial



# 2050 Values Assuming LCFS Progresses to 80% CI Reduction



# Tipping Fees

- Landfill disposal carries tipping fees (charge for disposing for material in the landfill) of $60 to $100
- Conversion facilities (bioenergy or composting) which replace this function can be expected to receive similar payments
- This study assumes a tipping fee of $60 per ton for landfill- diverted organic material (Jaffe et al. and developer input) – note that the tipping fee will likely increase if needed to meet the market price of fuel

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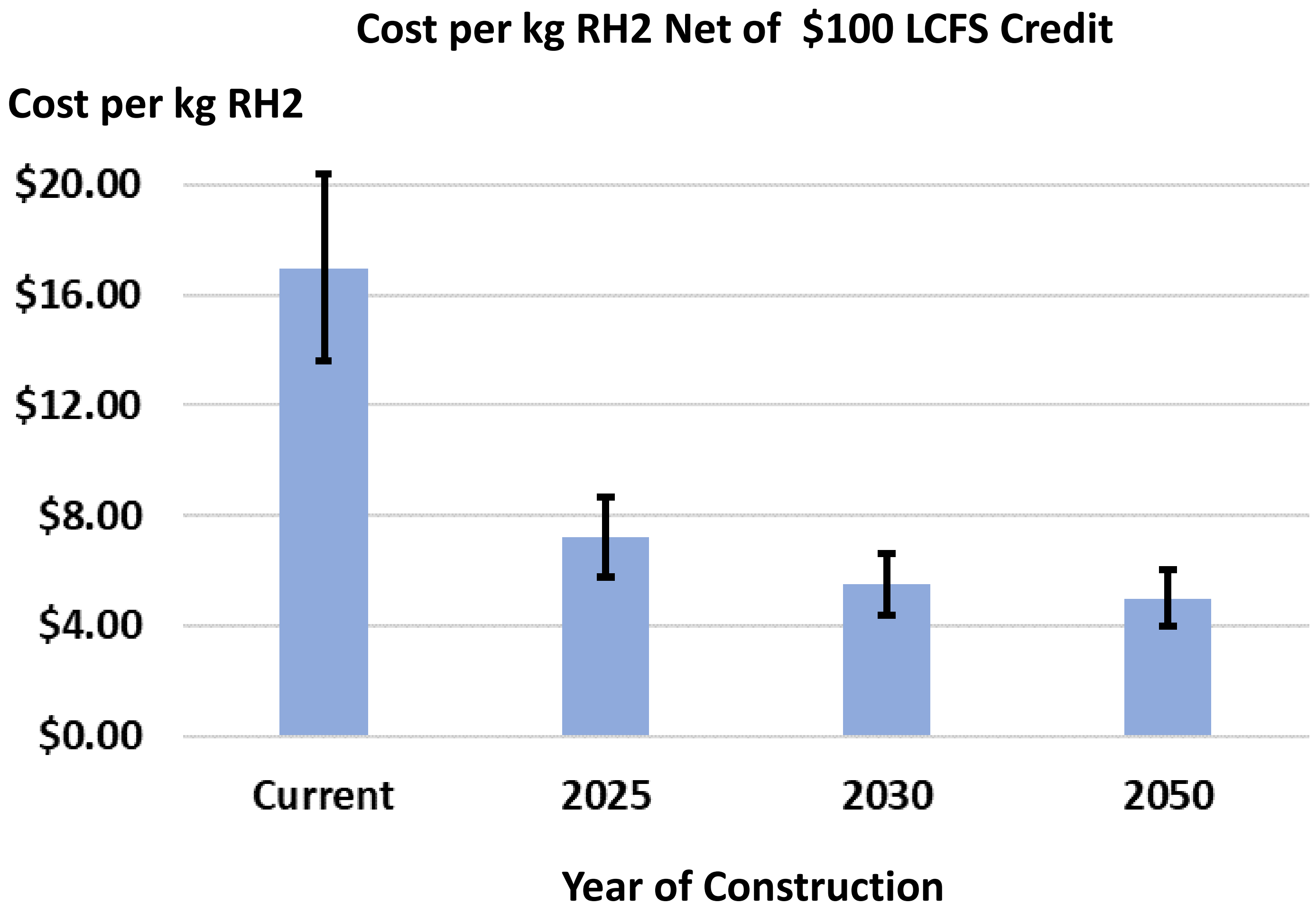
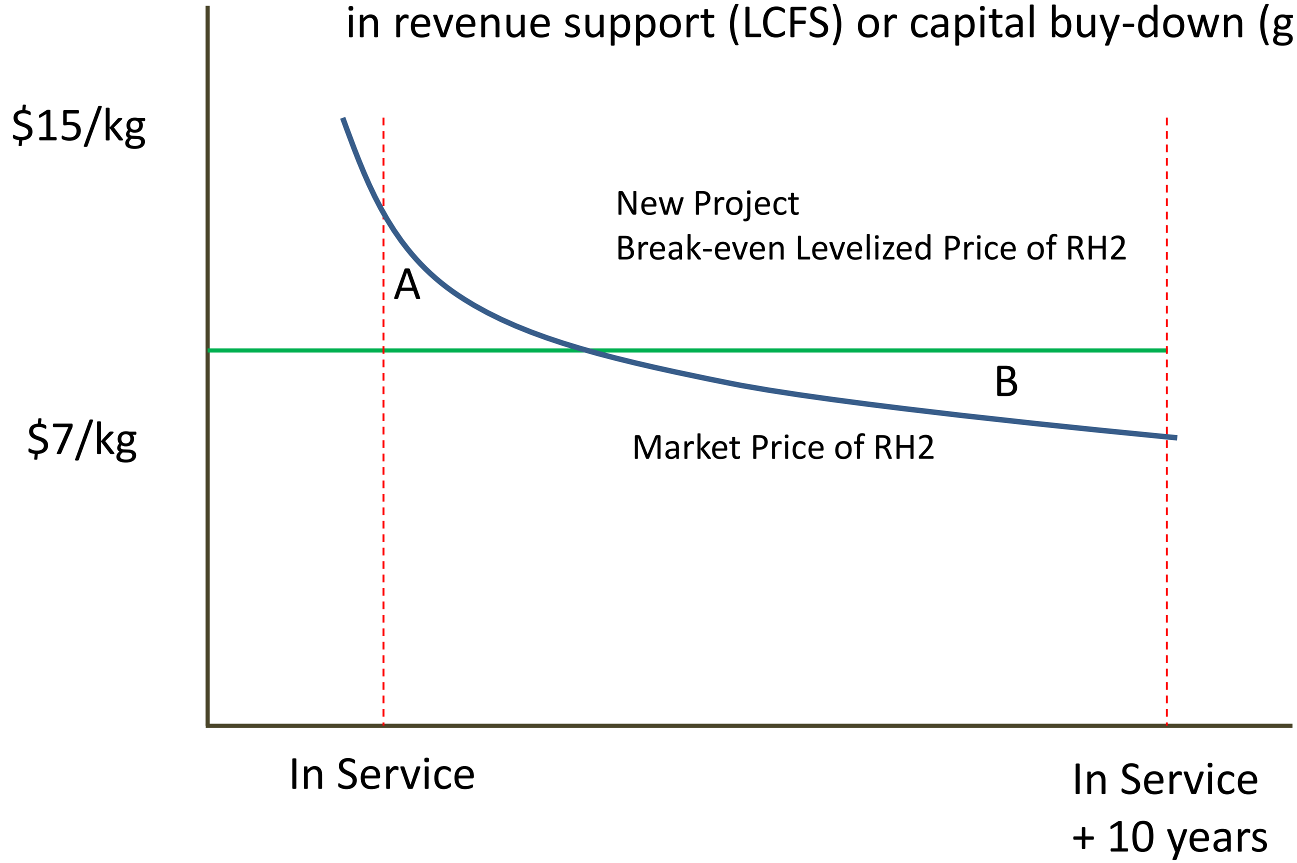
# Potential Evolution of Pump Price of Renewable Hydrogen



# “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)



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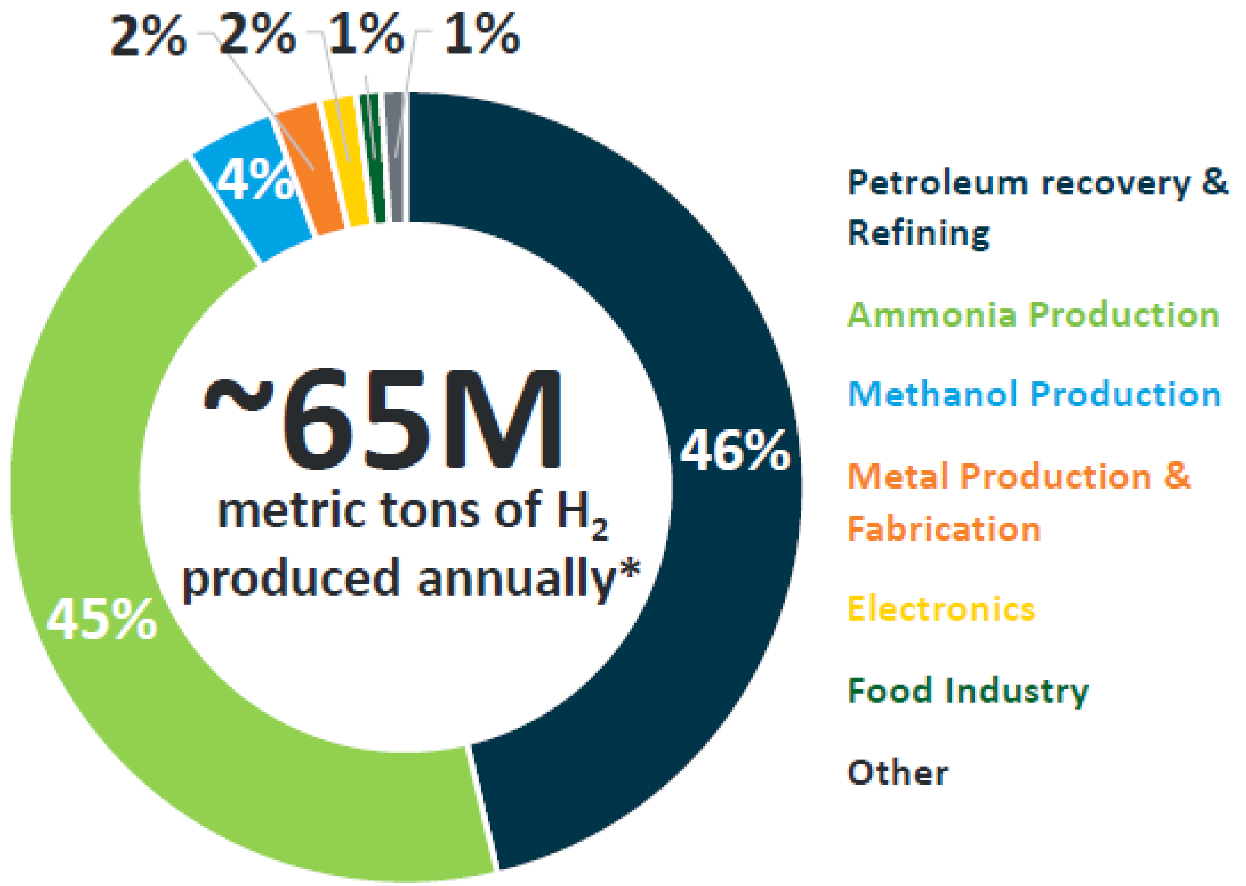
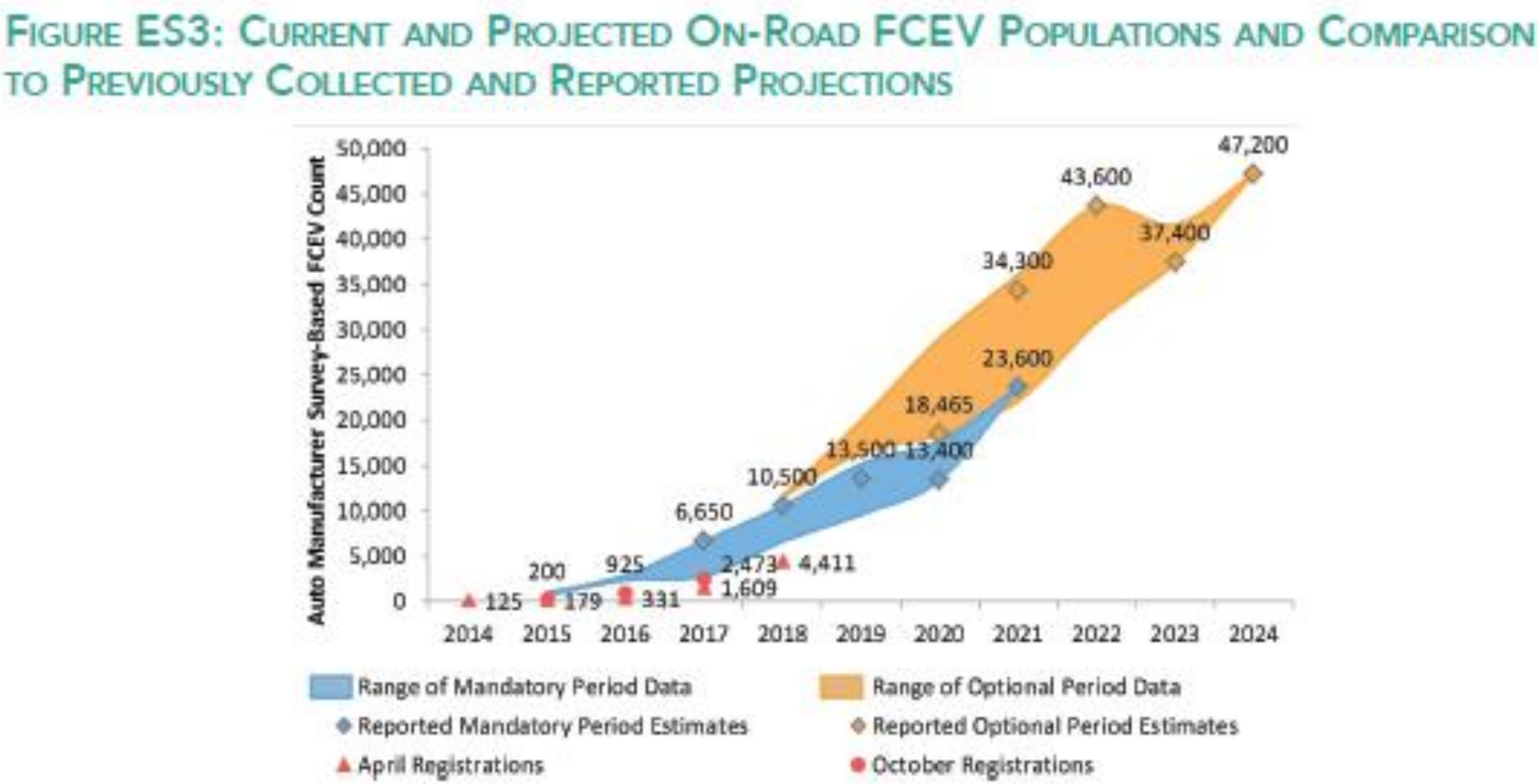
# Global Hydrogen Production and Demand




Source: (Satyapal 2017)

# Hydrogen Vehicles will Drive New Demand



# Other Transportation Demand Potential

- **Provide zero emissions fuel to difficult end-uses**

**Shipping**


**Aircraft**


**Fuel Cell Trains & Locomotives**

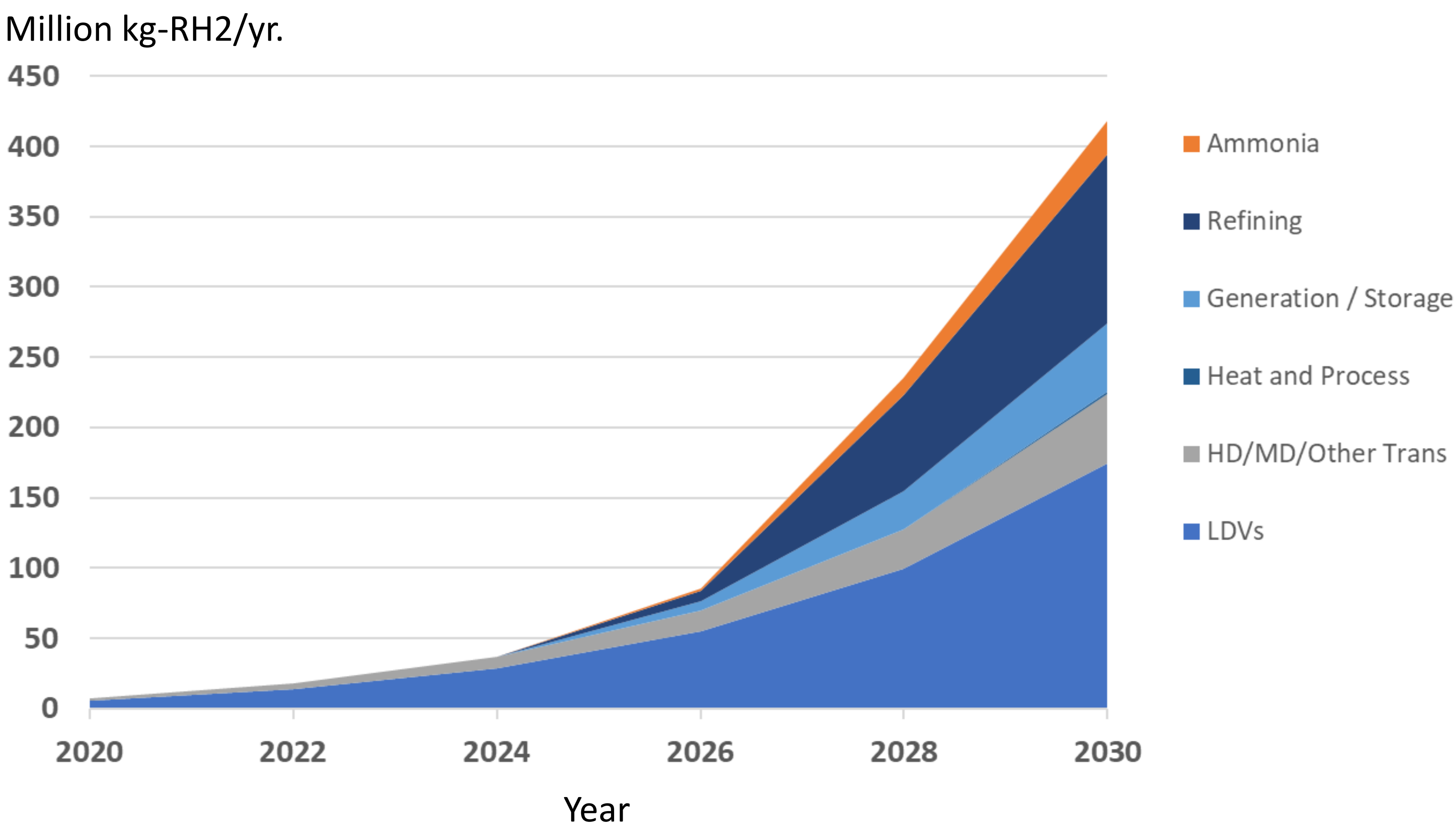
**Fuel Cell Buses**


**Toyota Fuel Cell:**
Zero Emissions Big Rig

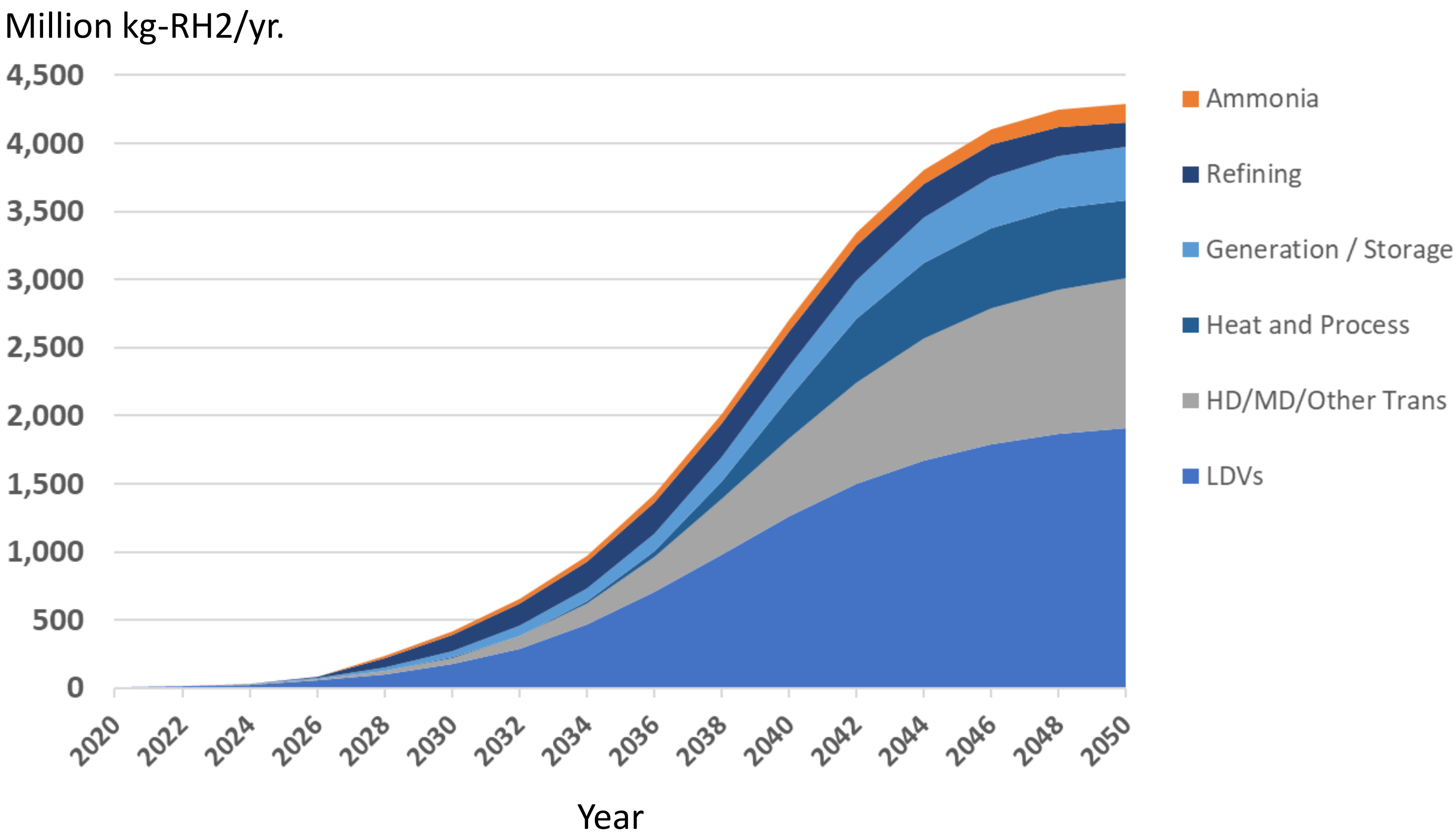
# RH2 Demand Scenario Assumptions

| RH2 Application | High | Low | Mid |
|---|---|---|---|
| Light-duty Vehicles | • 1 million FCEVs by 2030<br>• 50% penetration by 2050 | • 250,000 FCEVs by 2030<br>• 20% penetration by 2050 | • 500,000 FCEVs by 2030<br>• 35% penetration by 2030 |
| Medium Duty, Heavy Duty and other | • Hydrogen serves 50% of MD/HD renewable diesel demand in Vision 2.1 and 20% of "other" non-LDV | • Mobile Source Strategy Clean Vehicles and Fuels Scenario in Vision 2.1 | • Mid point between high and low |
| Process and heat | • 10% of current NG demand in 2050 with H2 blending beginning in 2025 | • RH2 serves transportation only | • 50% of high case |
| Generation and Storage | • Half of resource need from RESOLVE for geothermal and storage | • RH2 serves transportation only | • 50% of high case |
| Refining | • 100% decarbonized H2 by 2050 on linear ramp beginning 2025 | • RH2 serves transportation only | • 50% of high case |
| Ammonia Production | • 100% decarbonized H2 by 2030 | • RH2 serves transportation only | • 15% of high case |

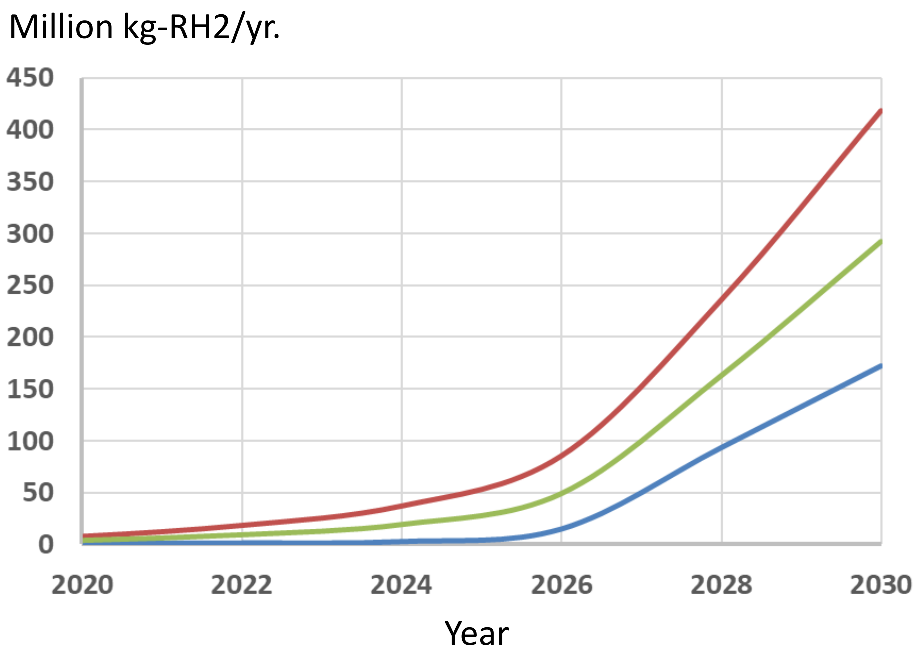
# High-Case California Renewable Hydrogen Demand to 2030

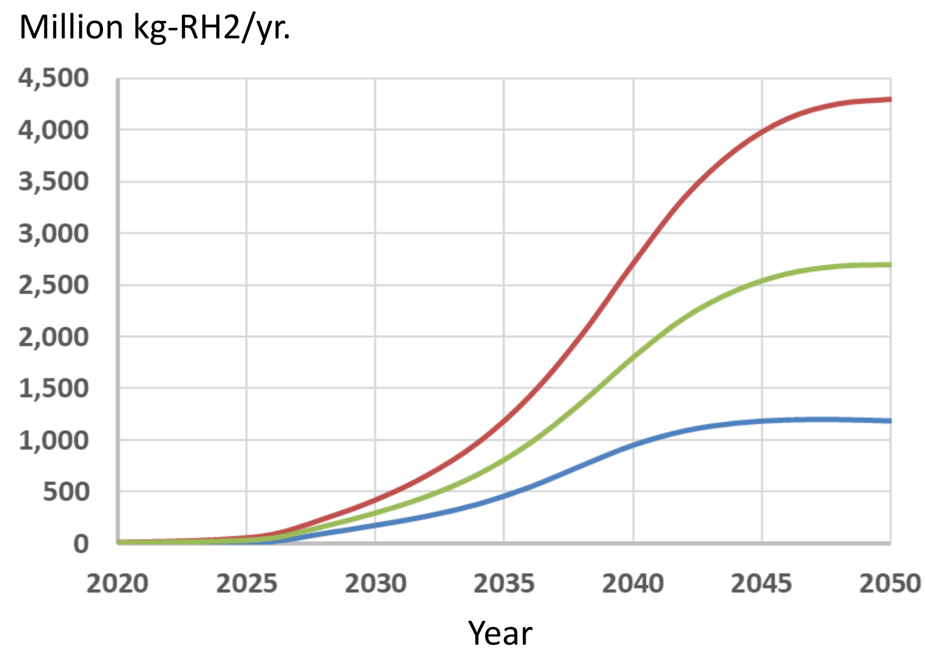


# High-Case California Renewable Hydrogen Demand to 2050



# Full Set of RH2 Demand Scenarios



# Agenda – Renewable Hydrogen Production Roadmap Review

- Overview and Summary
- Renewable Hydrogen Dispensed Cost Analysis
  - Primary Production (Conversion) Technology
  - Delivery Chain
  - Feedstock Cost and Supply
  - Credit and Tipping Fees
  - Dispensed Cost of Hydrogen Evolution
- Renewable Hydrogen Demand Analysis
- **Renewable Hydrogen Production Facility Build-out and Siting Scenarios**
- Project Recommendations and Research, Development and Demonstration (RD&D) Needs Assessment

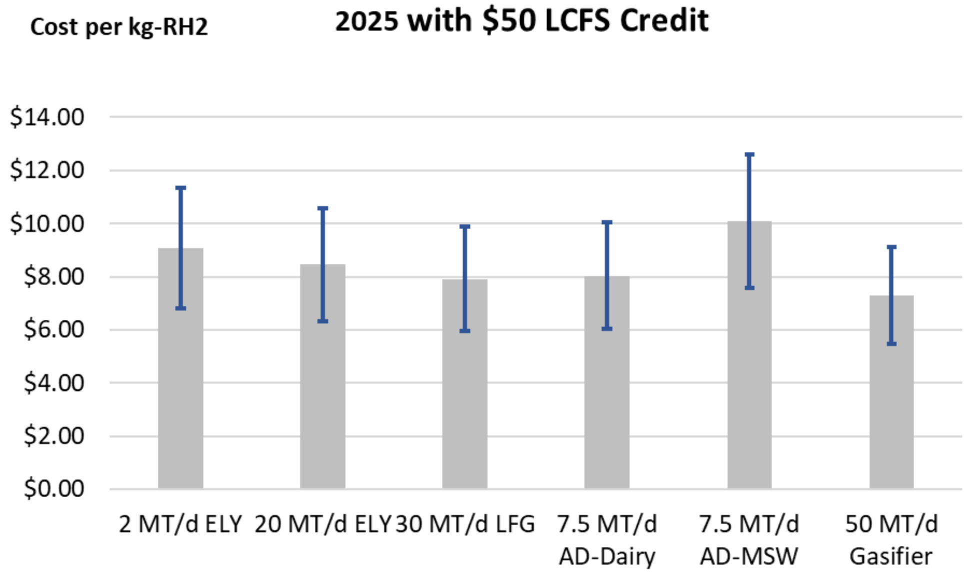
# Build Scenarios -- Context

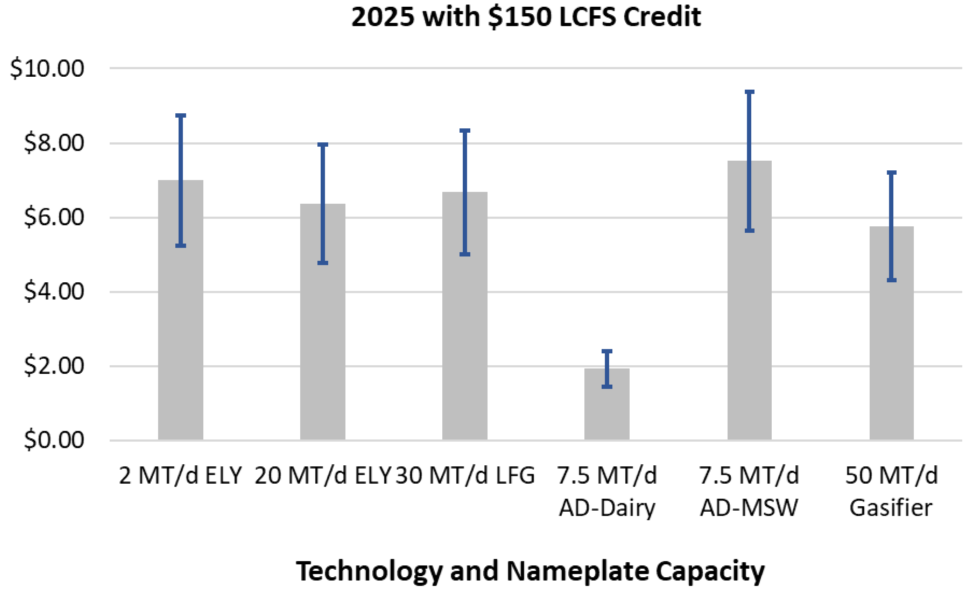
- Dozens of new renewable hydrogen production facilities will be needed to meet demand by 2030
- The mix of facility types cannot be forecast with certainty but all primary pathways will likely be represented
  - Reformed biomethane is the dominant pathway today and SMR capacity is expanding
  - 2 electrolyzers projects have been funded with others under development
  - Favorable projected gasification economics and policy priority on forest thinning to address fire risk expected to drive development
- This analysis does not specifically model import or export – these would reflect as changes to demand for in-state production
- Competing demand for biomass resources (RNG, liquid fuel and power production) is a primary source of uncertainty – RH2 is an attractive option for developers if off-take agreements can be secured due to EER advantage
- Independent of ultimate use (RH2 or other), policy mandates will drive the conversion of biomass to fuel

# Policy Drivers

- **Short-Lived Climate Pollutant Strategy (SLCP) places a major priority on dairy methane capture and conversion of landfill-diverted organics**
- **Highly negative carbon intensity, closed-ended incentives and the potential of future prohibition on dairy methane emissions a major forcing function for dairy biomethane development**
- **Landfill diversion mandated by statute**
- **Wildfire risk management likely to lead to mandates on forest management that require biomass harvesting**
- **The net conclusion is that most of the biomass resource potential in California will be developed with a major push prior to 2030 (driven by SLCP strategy)**

# Comparative Cost Range with Credits 2025

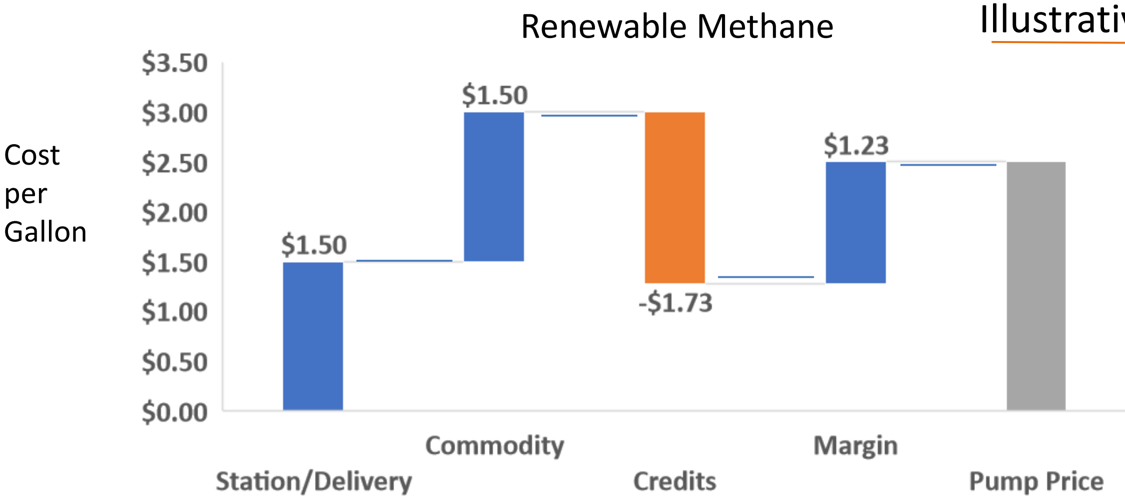


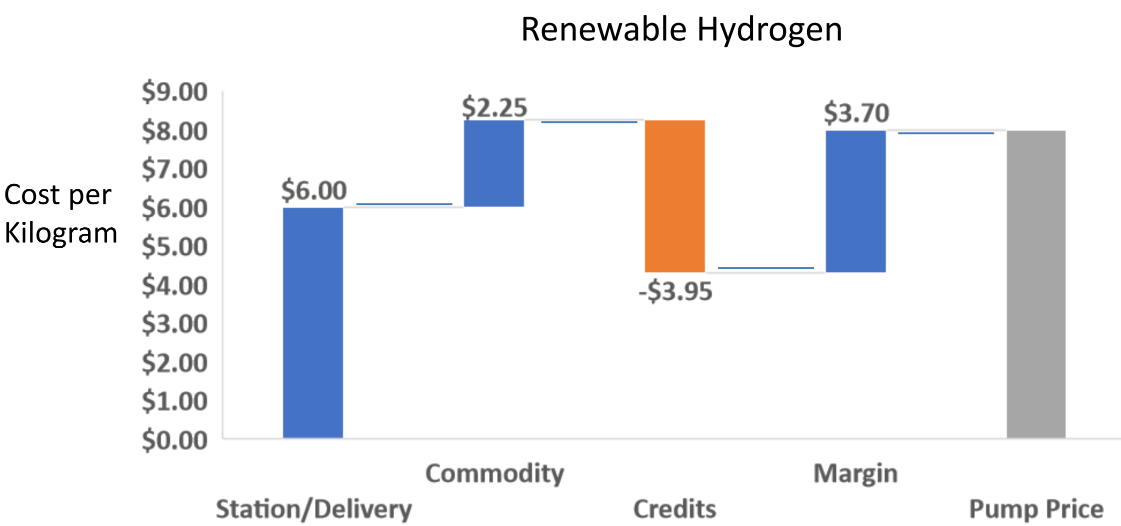




- **All technologies are within competitive band at both $50 and $150/ton LCFS credit value**
- **Gasification and landfill gas less dependent on LCFS credits**
- **Landfill diverted material may require higher tipping fees to compete effectively as an RH2 source**
- **Dairy has a strong advantage at higher credit values**

# RNG or RH2?

Illustrative



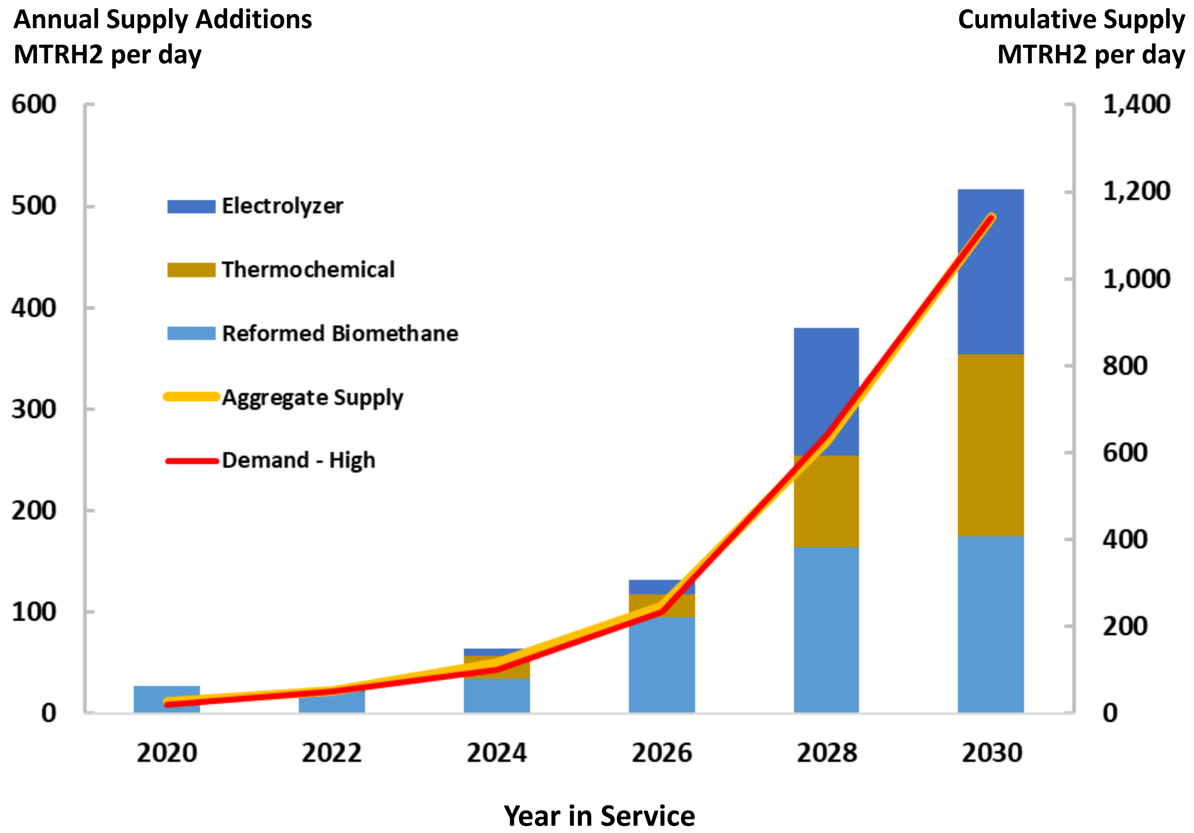




- **Hydrogen production and delivery costs are higher than for RNG**
- **However, the RH2 pump price likely to reflect the superior EER for hydrogen**
- **Higher EER also generates more credits**
- **The case illustration is for a CI of 20 in 2030 with the noted costs for commodity supply through dispensing and carbon credit value of $150 per credit**
- **Relative economics are closer as credit price decreases**
- **RIN credits reduce but do not eliminate the advantage of RH2**
- **Scenarios assumed demand for biomethane continues in both RNG and RH2 sectors – base case 50/50**

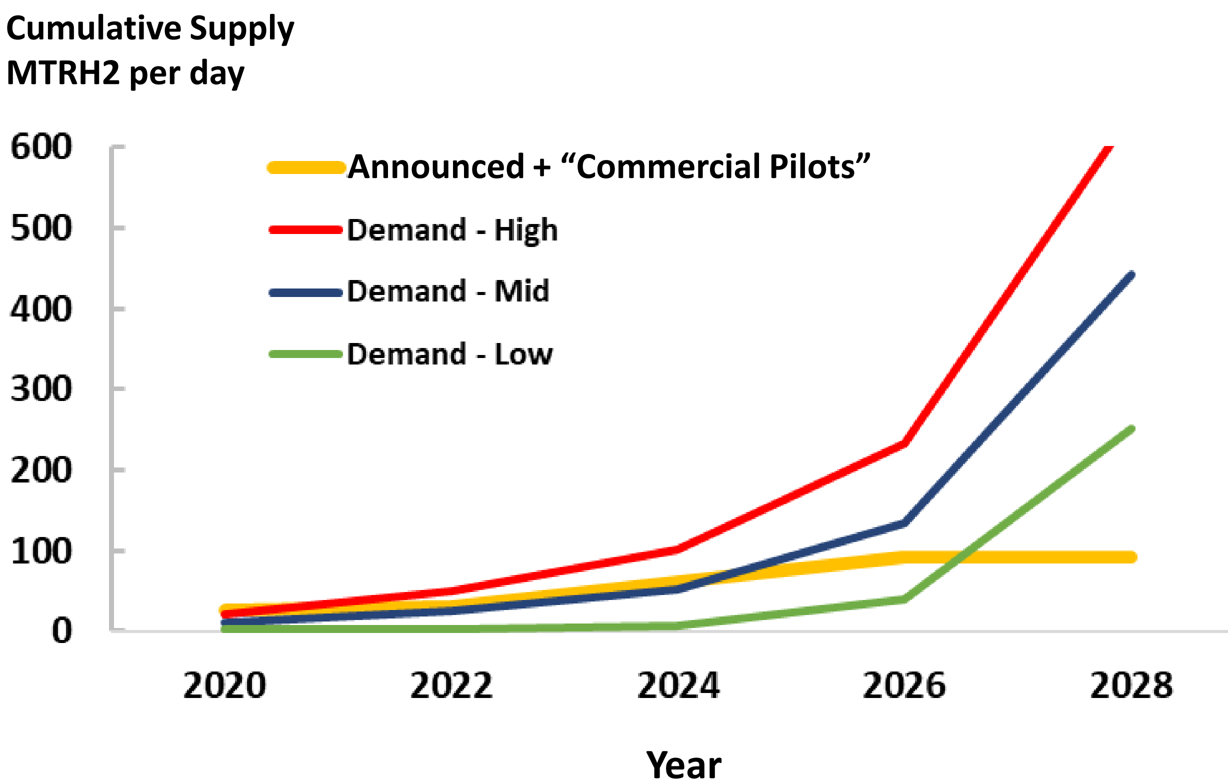
# Early Market

- The current RH2 market is predominantly served by reformed biomethane
- Thermochemical and electrolytic supply will be necessary to meet demand beginning in the late 2020's to early 2030's
- These technologies will not be ready to scale without policy-driven advance deployment – electrolyzers need learning to reduce cost and thermochemical (gasification) will need operating history to attract financing
- All roadmap scenarios assume state-sponsored electrolyzer and gasification projects
  - 5 x 5,000 kilogram per day + 2 x 10,000 kilogram per day of electrolyzer capacity
  - 2 x 25,000 kilogram per day of gasifier capacity
- Cost to the state of $80 to $120 million based on 50% capex subsidy or loan guarantees on 80% of project cost (in the case of gasifiers)
- Operating expense subsidy may not be required – marginal production cost may allow sales to the conventional hydrogen market if facility utilization is low

# Early-market Build-out Scenario – High-demand Case



# Supply-Demand Balance with Commercial Pilot Project Build

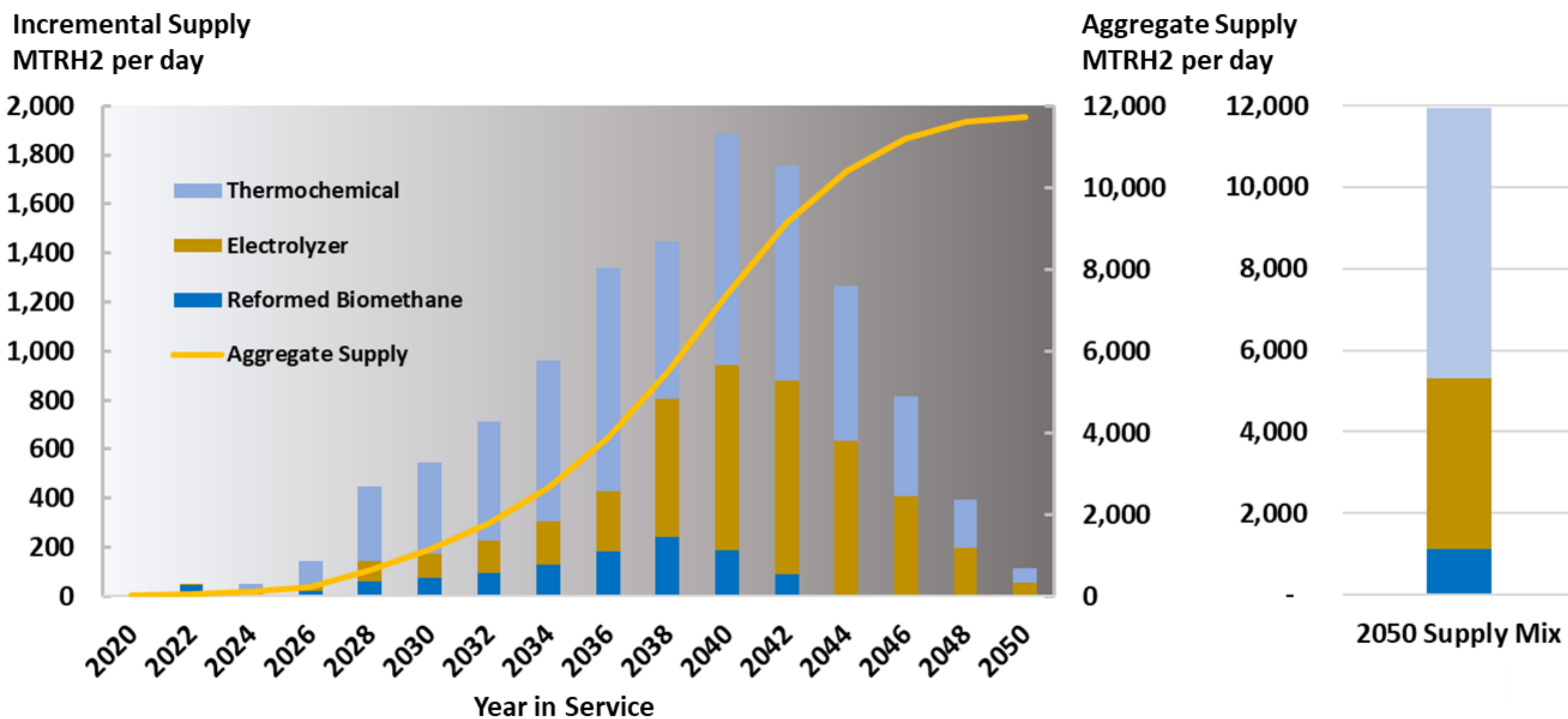



- **If only currently announced and the hypothetical set of state-supported (7 electrolyzer and 2 gasifier) projects are considered, additional capacity will be needed between 2022 and 2027 depending on demand scenario**

# Scenarios

| Scenario | Demand | Technology Cost |
|---|---|---|
| **Base-case (BC)** | Mid case | Base case for all technologies |
| **High-Demand (HD)** | High case | Base case for all technologies |
| **Low-Demand (LD)** | Low Case | Base case for all technologies |
| **High-electrolysis (HE)** | Mid case | Electrolyzer cost progression favorable relative to others (capital cost, efficiency, input electricity cost) |
| **High-thermochemical (HTC)** | Mid Case | Thermochemical conversion cost progression favorable relative to others (capital cost, efficiency, feedstock) |
| **High-anaerobic-digestion (HAD)** | Mid-case | 75% allocation of biomethane to hydrogen production (proxy for hydrogen value chain cost reduction) |
| **High-forecourt (HF)** | Mid Case | Forecourt solution cost progression favorable relative to central (capital cost, efficiency, electric rates, near-zero NOx mitigation for reformation) |

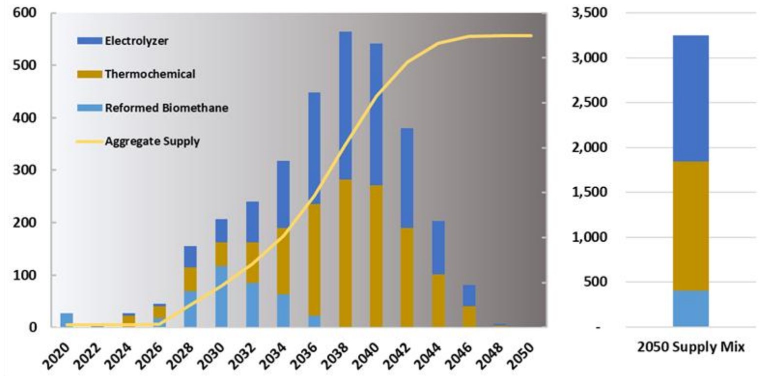
# Build-out to Serve High-demand Case




- Build-out to meet high-demand case assuming successful commercialization of thermochemical conversion technology (base case)
- On the order of 500 new facilities needed (depending on facility size) – more than 25 new facilities in the peak year
- Aggregate investment of **$30 - $50 billion**

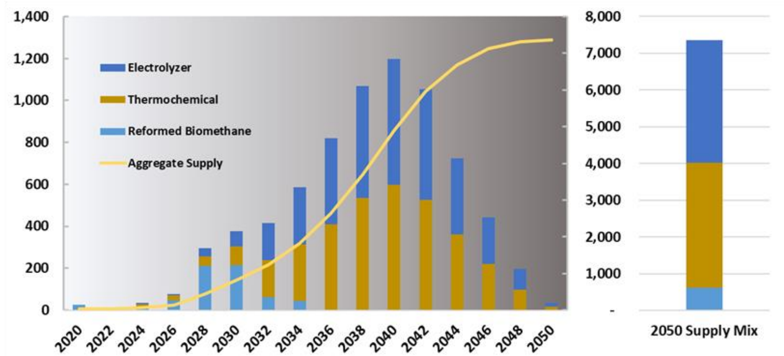
# Additional Build-out Scenarios

**Incremental** **Aggregate**

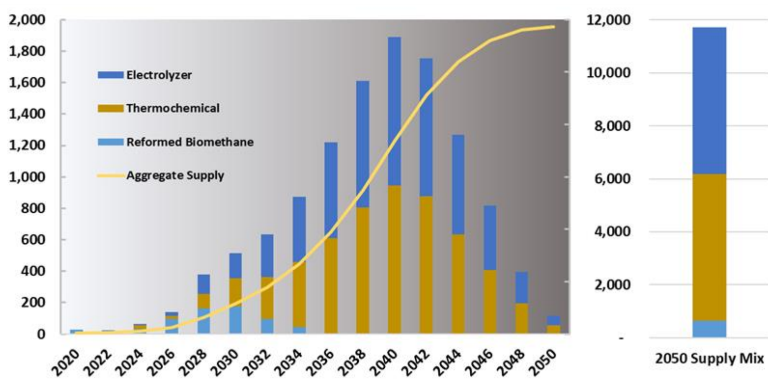



- **Low Case**

MT
RH2
Per
Day



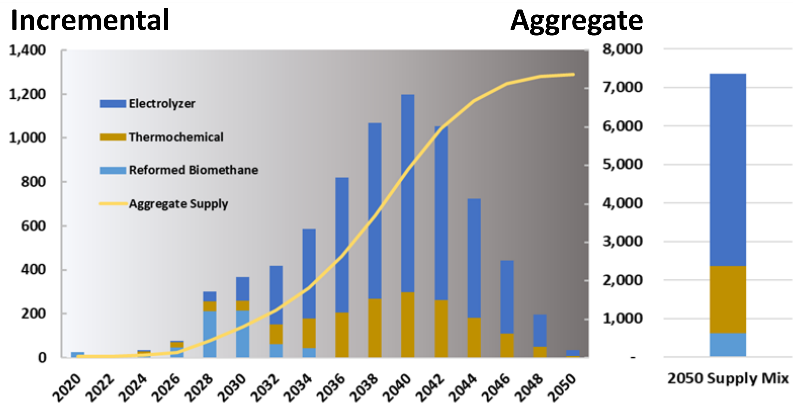

- **Medium Case**



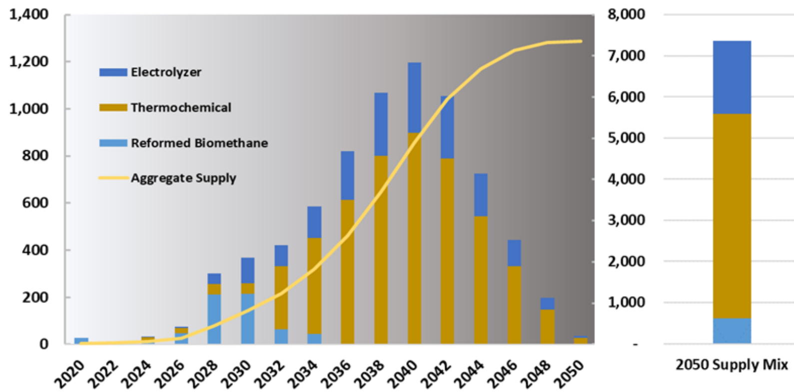

- **High Case**

# Additional Build-out Scenarios

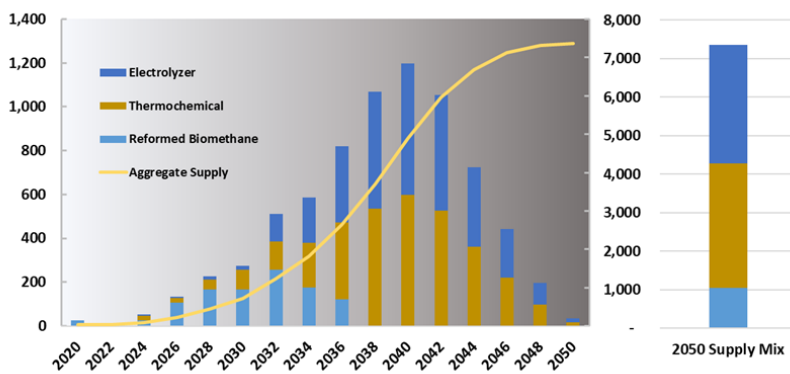
MT RH2 Per Day




- **High Electrolysis Case**




- **High Thermochemical Case**




- **High Biomethane SMR Case**

# 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 WRRF, permitted refuse facility or existing refuse route
- Proximate to natural gas transmission

**SMR (+ Liquefaction*)**

- Proximate to natural gas trans.
- Highway and/or rail access
- 10 acre site availability
- (Electric transmission access*)

**Thermochemical (+Liquefaction*)**

- Proximate to biomass resource
- Highway and/or rail access
- 10 acre site availability
- (Electric transmission access*)

Site section from among candidate sites based on cost minimization and community impacts

* If cryogenic liquid transport is used, liquefaction facility co-located with large host

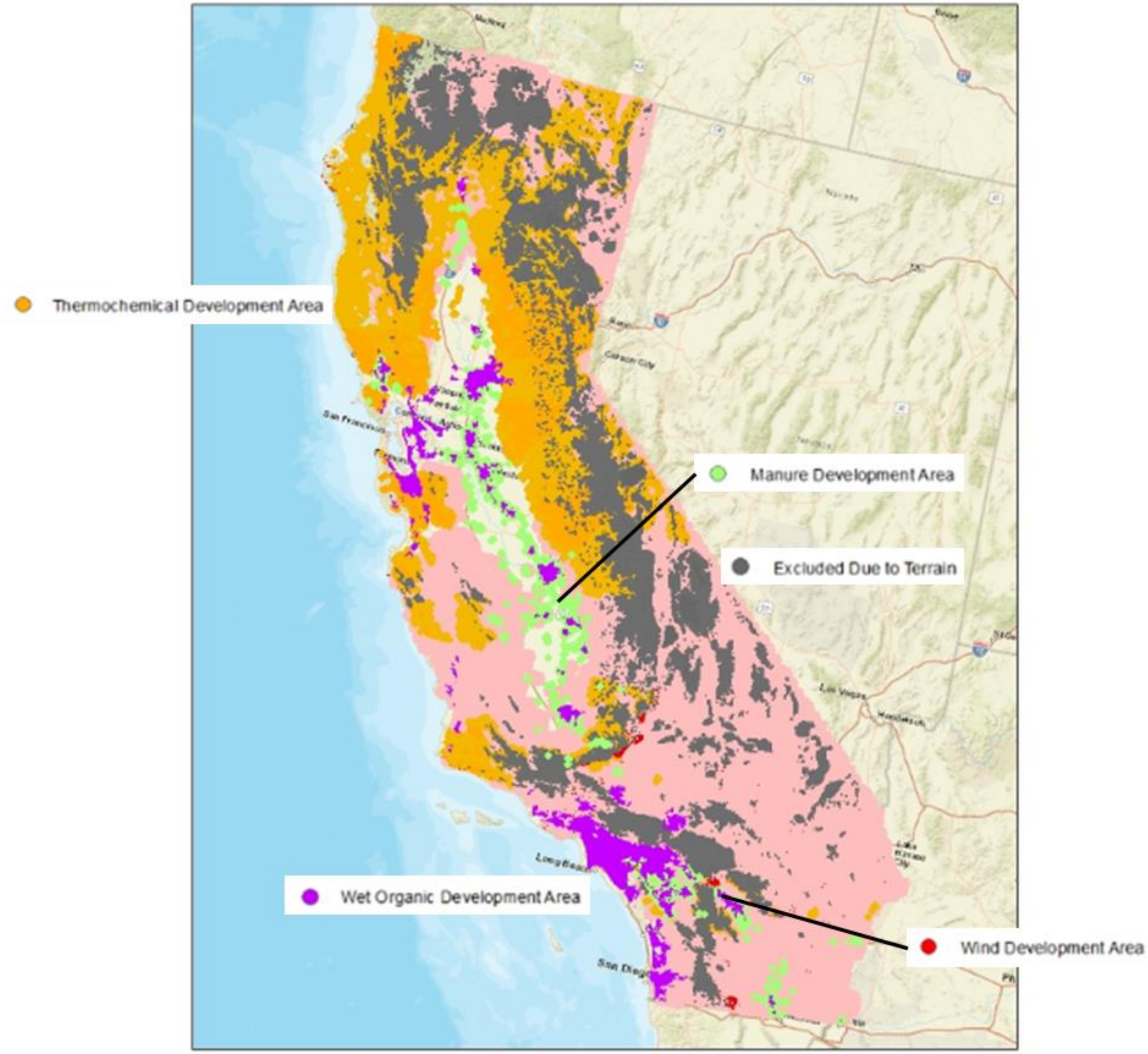
# Reference Facility Sizes

| Technology | Facility size (nameplate) | Comment |
|---|---|---|
| **Thermochemical conversion** | 50,000 kg RH2 per day | Size selected to achieve economic scale – larger facilities are possible but may have greater community impacts |
| **Anaerobic Digestion** | 7,500 kg RH2 per day | Based on current project activity |
| **Reformers (and associated liquefaction system)** | 30,000 kg RH2 per day | Reformers and liquefier assumed co-located<br>Size matches announced Air Liquide project |
| **Electrolyzer** | 20,000 kg RH2 per day | Based on manufacturer input on minimum efficient size for central production |
| **Forecourt Systems** | N/A | Sized based on the size and demand of host hydrogen refueling stations |

# Disadvantaged Community Considerations

- Siting of facilities in DAC areas has both positive and negative impacts
  - The main positive is job creation
  - Potential negatives include local air emissions, noise, visual impact and ingress and egress traffic
- In general, job creation in disadvantaged communities leads to net benefits
- However, significant NOx and/or PM emissions could override this
  - SMR and thermochemical systems are excluded from DAC non-attainment areas as a base case
  - However, advanced emissions controls and offsets could change this

# Primary Resource Development Areas



# Primary Demand Areas

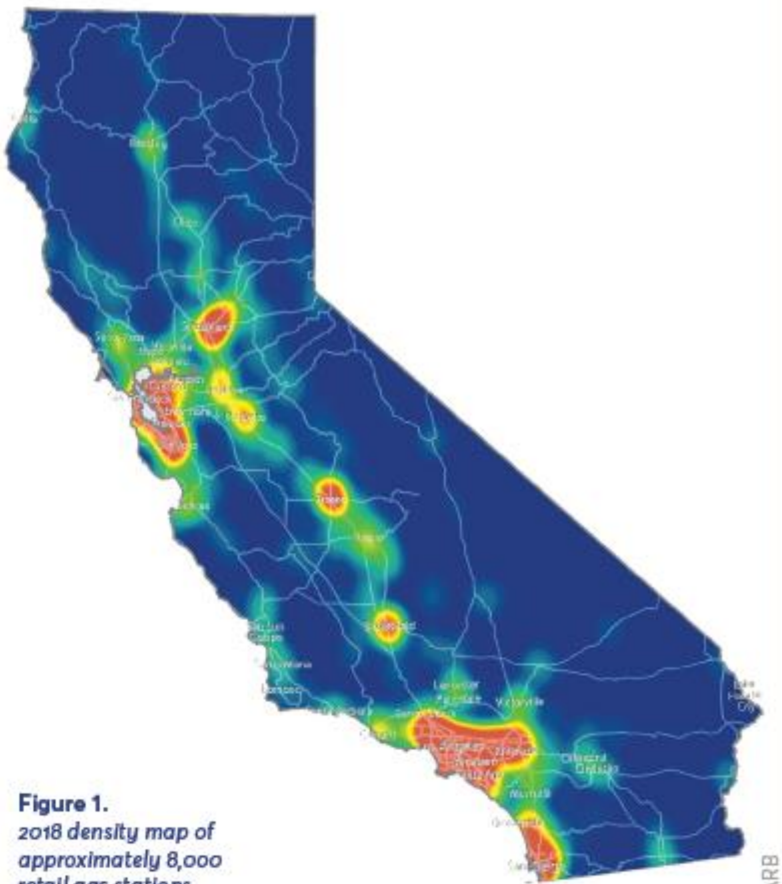



**Figure 1.**
*2018 density map of approximately 8,000 retail gas stations*

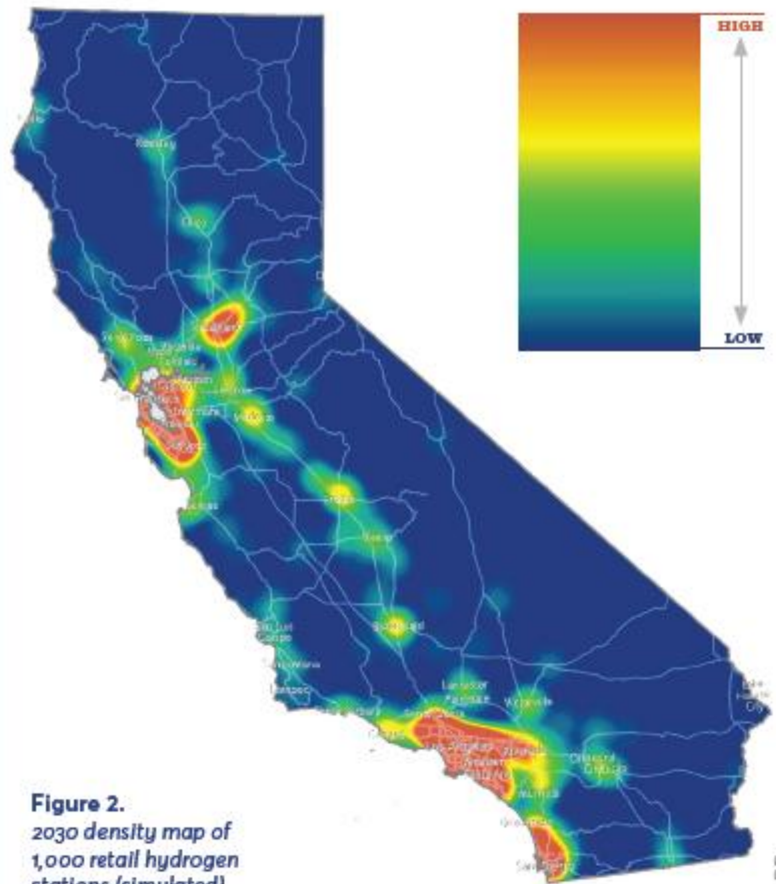


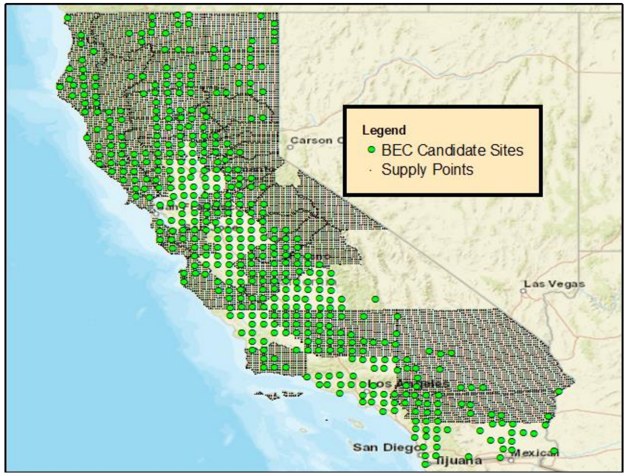

**Figure 2.**
*2030 density map of 1,000 retail hydrogen stations (simulated)*

# Map Layers Used for Siting Analysis



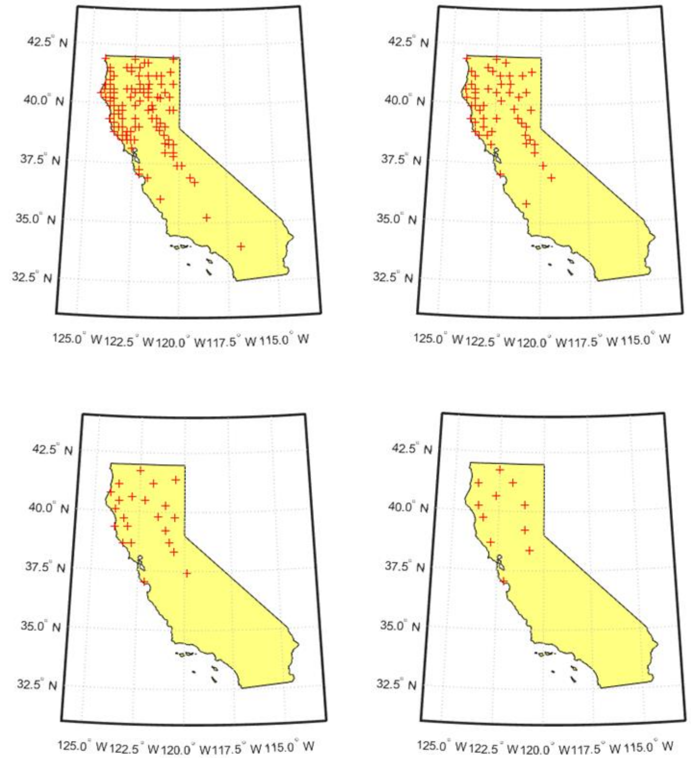


# Example Siting Analysis Result




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

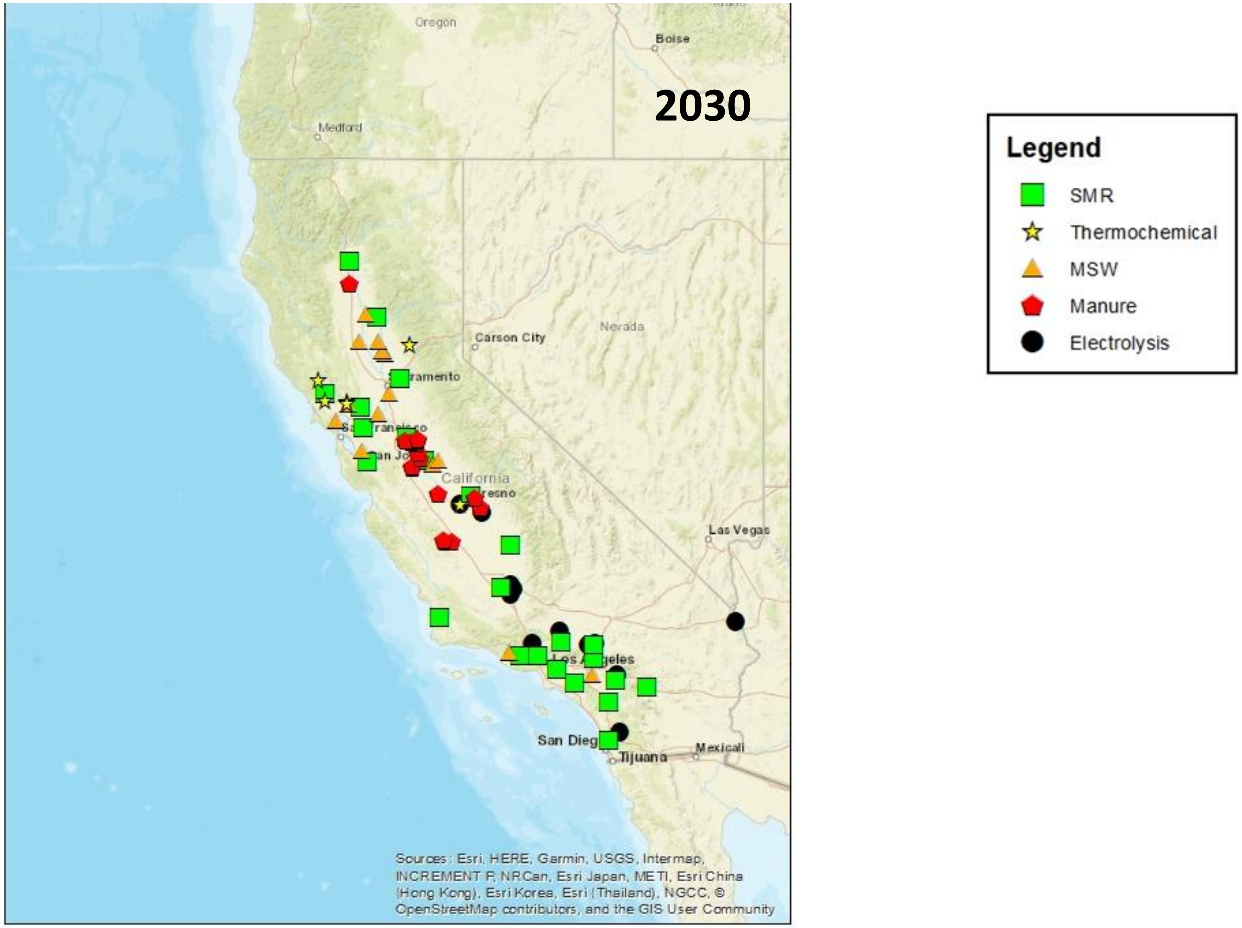
100 tons/day    200 tons/day



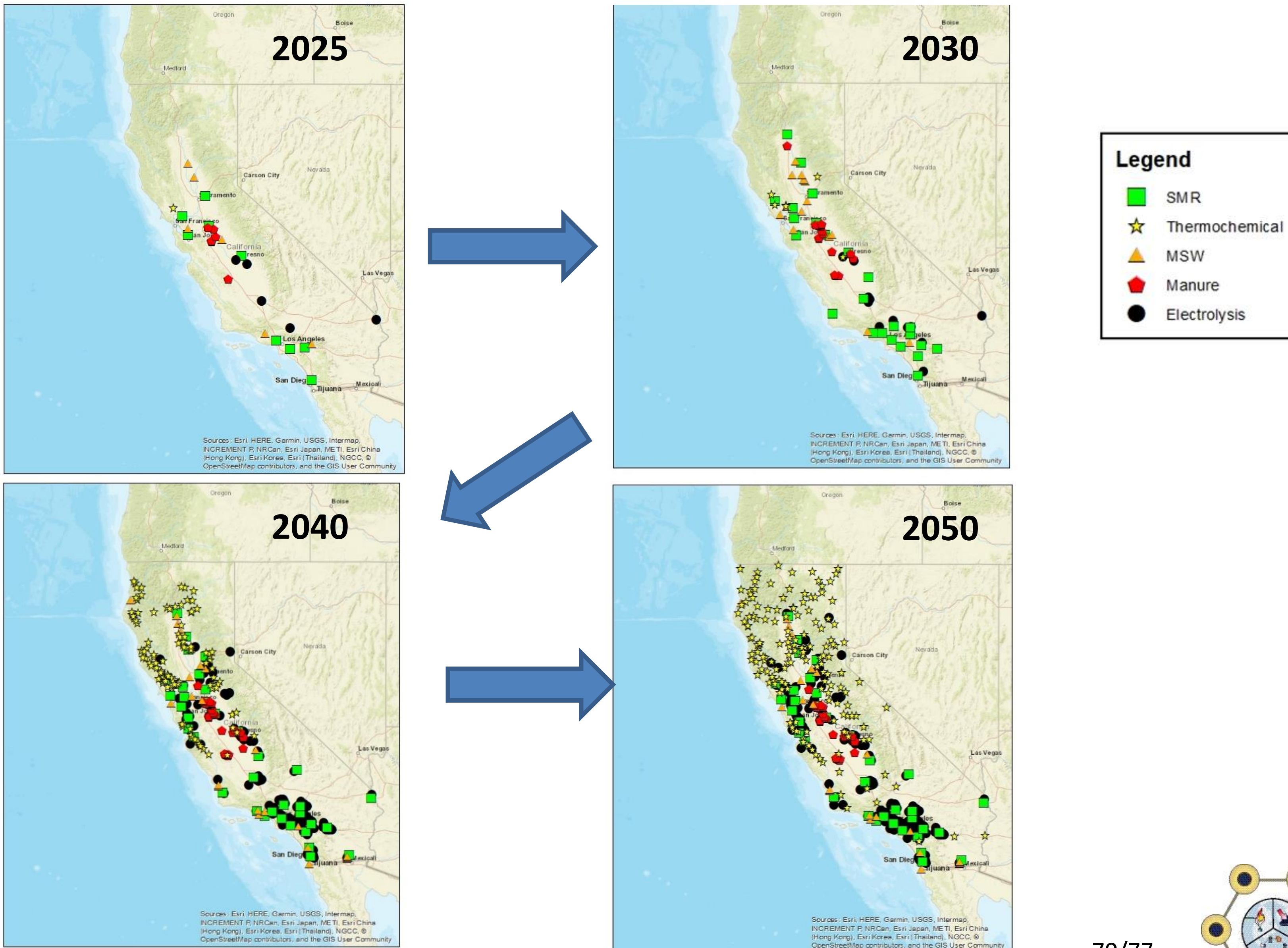

480 tons/day    960 tons/day

- **Optimization algorithm allocates facilities to available locations based on total demand and facility size to minimize cost of combined road and rail delivery to demand areas**

# High-Demand-Case 2030 Scenario



# Representative Temporal and Spatial Build-out



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# Project Recommendations

1. Extend hydrogen infrastructure support to the entire supply chain
   - Station program successful and well established
   - Initial funding program in place for production
   - Plant-to-station carries about 1/3 of the cost and may need support also
2. Take steps to support a smooth expansion of production capacity that keeps pace with demand
   - Well publicized demand forecasts
   - Tracking of project announcements and forecasting of long/short supply
   - Aggregate volume of incentives aligned with market expansion need
3. Focus on forms of support that attract private capital and support development of robust markers
   - Debt or loan guarantees have proven successful (DOE)
   - First-unit project need special support to create operating history – particular challenge for big-ticket projects
   - LCFS price support mechanism would improve project credit profile (secure revenue stream)
   - Support price and cost transparency (discovery)
   - Consider expansion of market participation in award of incentives
4. Reduce barriers to development in California -- e.g. Program Environmental Reports, integrated permitting support

# Project Recommendations

5. **Design programs and incentives holistically across fuel types -- pathway-specific incentives risk skewing optimal allocation of biomass feedstocks among RNG, RH2 and liquid fuels – e.g. federal RINs and proposed LCFS support mechanism**
6. **Establish electric rate structures specific to transmission-connected renewable fuels facilities (e.g. electrolyzers and liquefaction facilities) such as wholesale power market access + transmission charge**
7. **Facilitate access to the natural gas system for renewable hydrogen transport and storage – establish blending limits and interconnection requirements**
8. **Take steps to ensure that a mixed gas / liquid supply chain does not create barriers to market access – e.g. provide incentives for development of open access points of entry to the supply chain such as gaseous or liquid terminal facilities**
9. **Ensure that renewable hydrogen development advances Social Justice**
   - **Research perceptions and priorities**
   - **Calibrate how job creation should be weighed against other factors**
10. **Act to ensure that program eligibility, environmental accounting and lack of definitions are not barriers to renewable hydrogen development (e.g. "renewable gas", "zero-carbon", "low-carbon"**
11. **Increase RD&D to support market development (following pages)**

# Research, Development and Demonstration Needs Assessment

- The RD&D needs assessment is a qualitative assessment of the need for future work related to RH2 identified during the course of the project
- The identified needs are additional to ongoing activity in California and at the DOE of which the research team is aware
- It is assumed that early-stage RD&D will continue to be adequately funded and directed by the DOE
- Some RD&D themes that are of specific importance to California and maximize leverage and synergy with DOE research include:
    - Cost and performance tracking and forecasting of renewable hydrogen production facilities and supply chain infrastructure to guide investor and policy-maker decisions
    - Global and California-specific demand forecasting to anchor technology forecasts and investment planning
    - Quantification of the value of sector coupling enabled by renewable hydrogen between the transportation, electric and natural gas systems
    - Development of optimal electric and gas rate structures and market designs as they relate to renewable hydrogen
    - Full-scale commercial demonstration of high-impact-potential technologies such as gasification and novel technologies across the production and supply chain, particularly those supporting production and storage at the station scale
    - Stakeholder research and engagement in the unique context of California policy environment and its position as a global early adopter of hydrogen solutions

# RD&D Needs

- Renewable Hydrogen Production Technology and Feedstock Supply
  - As-built and operational data collection and analysis
  - Assessment of the potential role of energy crops for the California renewable fuels sector
  - Potential impact of emerging renewable hydrogen production technologies
  - Potential role of carbon capture, utilization and storage in the renewable hydrogen production sector
  - Organic feedstock allocation based on fuel pathways cost and carbon intensity forecasting
- Demand, Adoption and Impacts Analysis
  - Analysis of global market growth in RH2 to support learning curve analysis
  - Economic adoption modeling for renewable hydrogen solutions
  - Public and key stakeholder perceptions
  - Continuity of Supply and Supply-chain Reliability
  - Air Emissions and other Community Impacts Analysis

# RD&D Needs

- **Supply-chain Forecasting and Optimization (Plant Gate to Point of Use)**
  - **Rigorous design basis and footprint analysis for on-site solutions**
  - **Down-scaling liquefaction and reformation**
  - **Mixed gas-liquid supply chain integration and optimization**
  - **Transition to dedicated pipeline transport for renewable hydrogen**
- **Renewable Hydrogen Fuel Production and Electric Grid Integration and Joint Optimization ("Sector Coupling")**

# Forthcoming

- **Project final report and appendices detailing the above material in narrative form with sources and methods**

- **Renewable Hydrogen Production Roadmap for California – separate document outline key findings in an abbreviated and simplified "white paper" format**

# Thank You.  Questions and Comments?

#RH2@APEP

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