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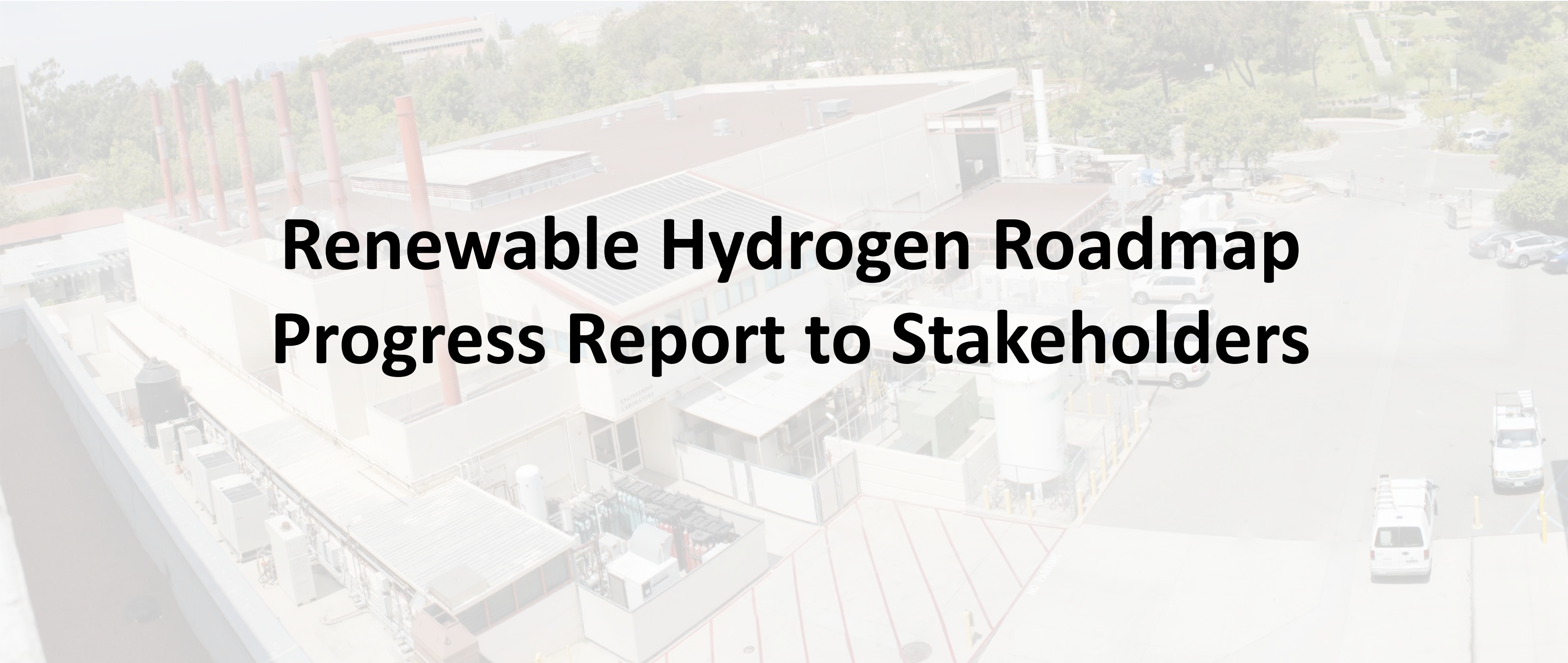
Presentation - Renewable Hydrogen Roadmap Progress Report to Stakeholders

Additional submitted attachment is included below.



Renewable Hydrogen Roadmap Progress Report to Stakeholders

ADVANCED POWER & ENERGY PROGRAM
UNIVERSITY of CALIFORNIA · IRVINE

November 13, 2018

Renewable Hydrogen Production Technology Assessment

I. Goals and Approach

II. Technologies covered

   a. Electrochemical

   b. Thermochemical

   c. Anaerobic Digestion with Reformation

III. Technology Cost Assessment and Forecasting Approach

IV. Cost and Performance Assessment and Forecasting Results

V. Approach to Modeling Costs for Transportation through Dispensing

VI. Status of Other Roadmap Tasks

VII. Questions and Comments

Renewable Hydrogen Roadmap Project Goals

- To provide specific guidance on actions needed to ensure success over the next 5 years in establishing the foundation projects for renewable hydrogen (RH2) production to serve the growing Fuel Cell Electric Vehicle (FCEV) market
- Maximize insights and lessons learned from first-generation RH2 projects
- Project cost evolution, aggregate investment and funding support needed to reach self-sustainability based on pump price and credit value scenarios
- Provide a high-level ("20,000 foot") roadmap through 2050 as a foundation for further refinement
- Maximize value and leverage of prior and ongoing work including the DOE H2@Scale initiative
- Engage industry stakeholders to validate conclusions and findings
- 1 year effort to conclude in June / July 2019

General Flow of Work Packages

Task 2

Technology Cost and Performance

- Reports and academic research
- Bid documents / Developer input

Feedstock Cost and Availability

- Published studies (e.g. Davis, BT2)
- H_2/CH_4 allocation scenarios
- Electricity costs from RESOLVE

Siting Constraints

- Footprint and emissions
- Zoning
- Access to feedstock, infrastructure and demand points
- DAC screen

Renewable Hydrogen Demand Evolution

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

Task 3

Siting Analysis -- Production and Delivery Chain Options

- Candidate sites by technology and grid location
- ArcGIS geospatial model layers and supply / demand heat maps

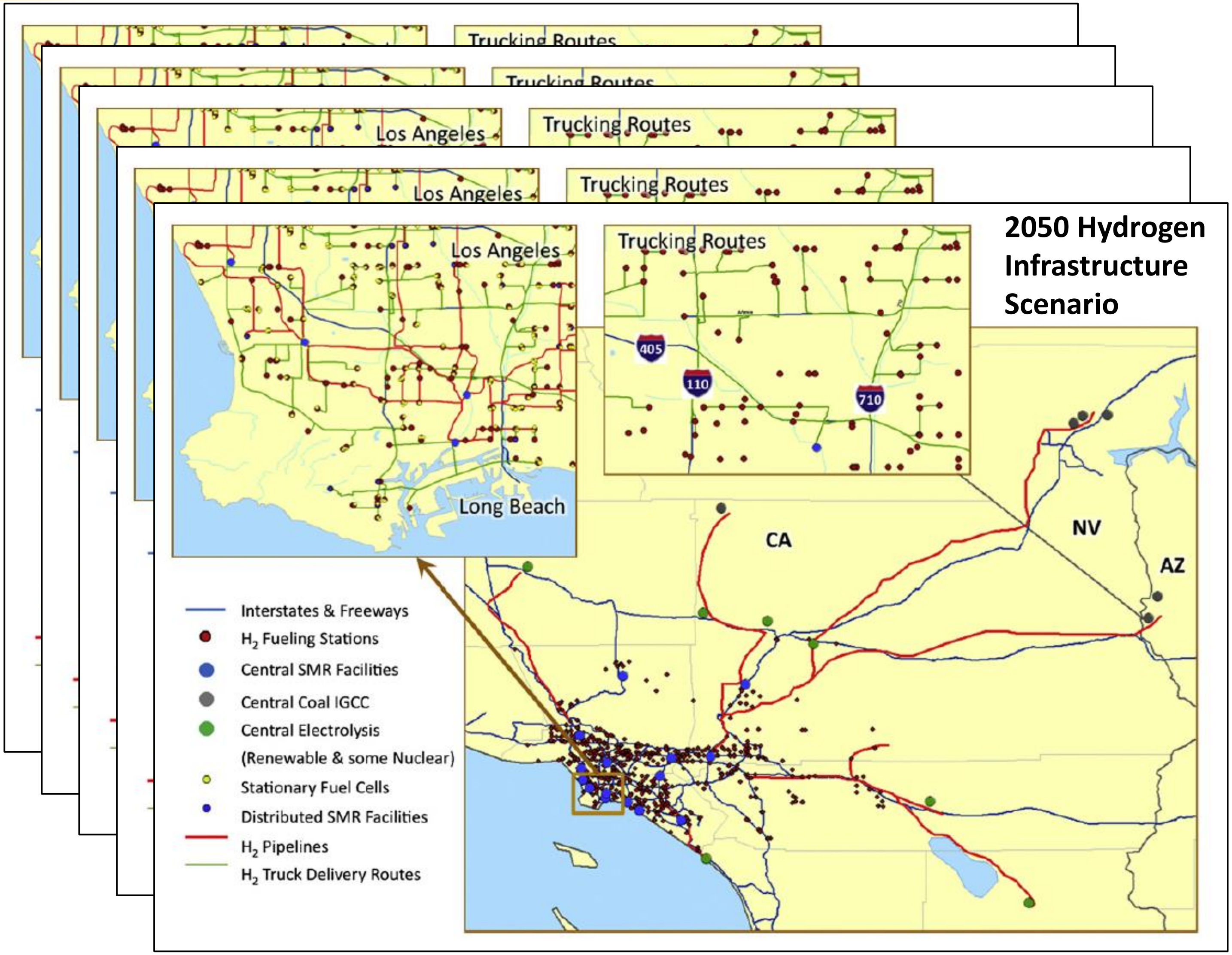
Task 4

Integrated Renewable Hydrogen Roadmap

- Spatial and temporal build-out scenarios (starting from existing and planned projects)
- High-level optimization and build sequencing
- Aggregate investment and RH2 cost projections
- Barriers, enablers and policy needs
- Future research needs

Task 1: Agreement Management (Reporting and Deliverables)

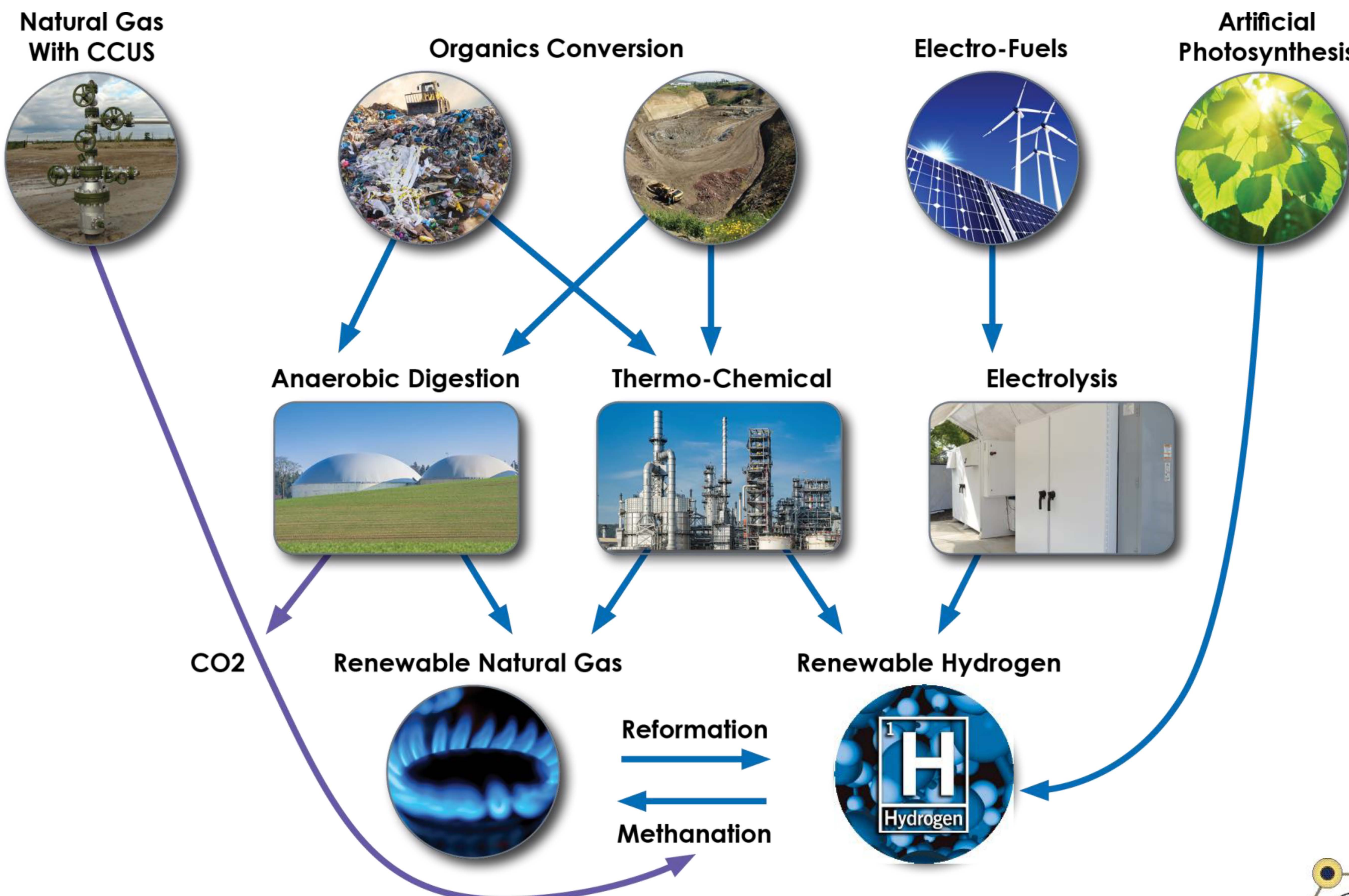
Time-Phased Renewable Hydrogen Deployment



Source: Projecting full build-out environmental impacts and roll-out strategies associated with viable hydrogen fueling infrastructure strategies. Stephens-Romero S.; Brown, T.; Carreras-Sospedra, M.; Kang, J.; Brouwer J.; Dabdub, D.; Recker, w.; Samuelsen, G. S.; Int'l Journal of Hydrogen Energy, 2011

Interim Results

Renewable and Zero-Carbon Gas Pathways



Stakeholder Engagement

- **Roughly 30 stakeholder interviews planned**
- **20 interviews completed spanning the supply chain:**
  - **Technology Vendors**
  - **RH2 Project Developers**
  - **Industrial Gas Companies**
  - **Hydrogen Station Developers**
  - **Consulting Engineers**
  - **Utilities**
- **Additional interviews to be conducted through end of December**

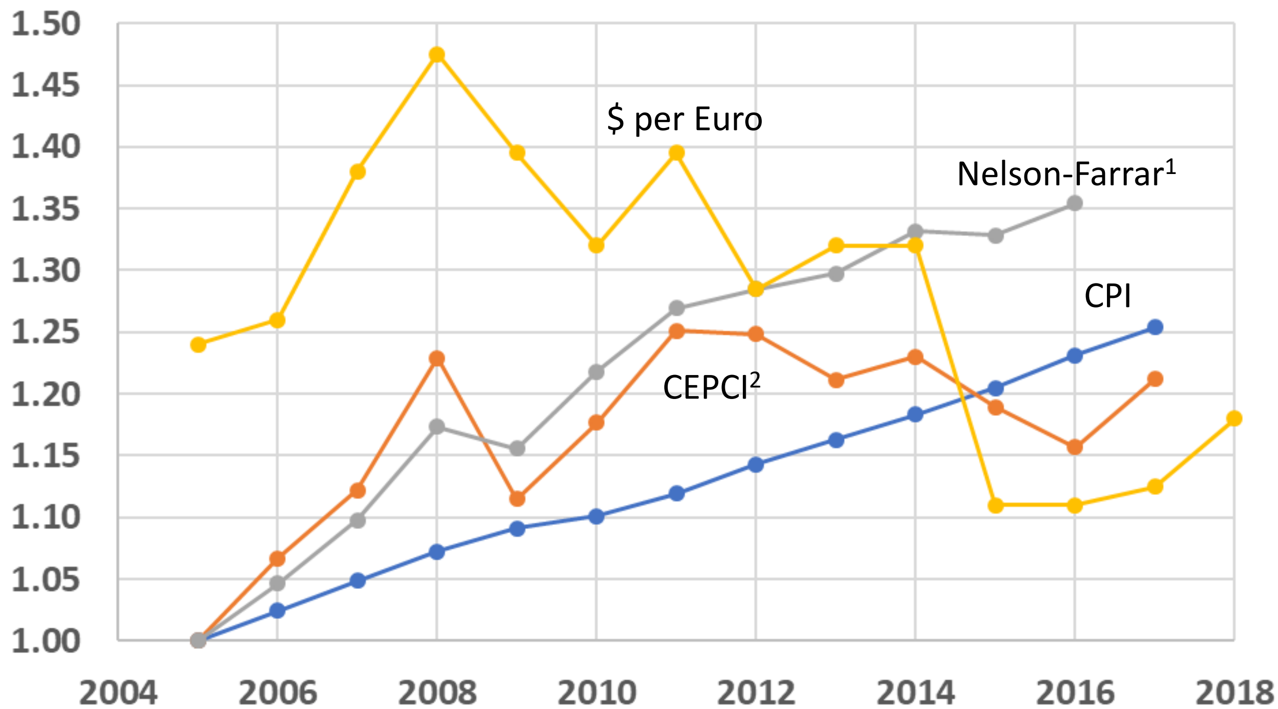
Interview Topics and Preliminary Themes

Topic Area	Themes
Market Evolution	• Market has “launched” but needs to scale • Most parties rely on CaFCP forecasts (upper scenario of 1M FCEV by 2030) but recognize the potential importance of applications beyond light duty vehicles particularly MD/HD
Ability to Meet Long-term Goal of $4/kg dispensed	• $2/kg uncompressed at the plant gate is challenging but possible with scale and R&D • Building scale (project and sector) is the key to cost reduction • All-in cost of $4/kg very challenging but cost-per-mile parity ($6 - $8/kg dispensed) is within range by 2025 to 2030 (net of LCFS value) and around $10/kg in the next project generation
Best Pathways in the “End Game”	• Diversity of views but most see a mix of technologies with both central and localized deployment • Strong trend toward LH2 supply chain
Barriers / Issues	• Uncertainty in LCFS credit values and in the pace of growth in demand for renewable hydrogen • Lack of reliability of supply could stall market acceleration • Need for sustained government support across budget cycles • Lack of access to low-cost renewable electricity as feedstock • Limited supply of biomethane for SMR pathways • Permitting challenges (depending on technology and location)

Profiling Current Cost and Performance

- Current cost and performance (conversion efficiency) were assessed using a variety of sources
    - Published academic papers
    - Agency reports and tools (such as National Energy Research Center (NREL) reports and Hydrogen Analysis Tool (H2A) case studies
    - Publicly available data from CEC solicitations
    - Stakeholder interviews
- There is significant variation on reported costs due to a variety of factors including:
    - Differences in the equipment sets used and included in the reported costs
    - Varying methods used to estimate project costs (prior actual costs, bottom-up estimate using bids or costing references, combination)
    - Inclusion or exclusion of indirect costs (engineering, permitting, site prep) (order of 20% of total cost)
    - Inclusion or exclusion of “Nth Plant” adjustment (order of 25% factor)
    - Uncertainty in cost indexation (choice of cost indices used to normalize cost estimates made at different times)
    - Uncertainty in scale factors used to normalize costs of plants of differing size
- Non-cost parameters show less variation in reported and forecast values

Normalization Indices

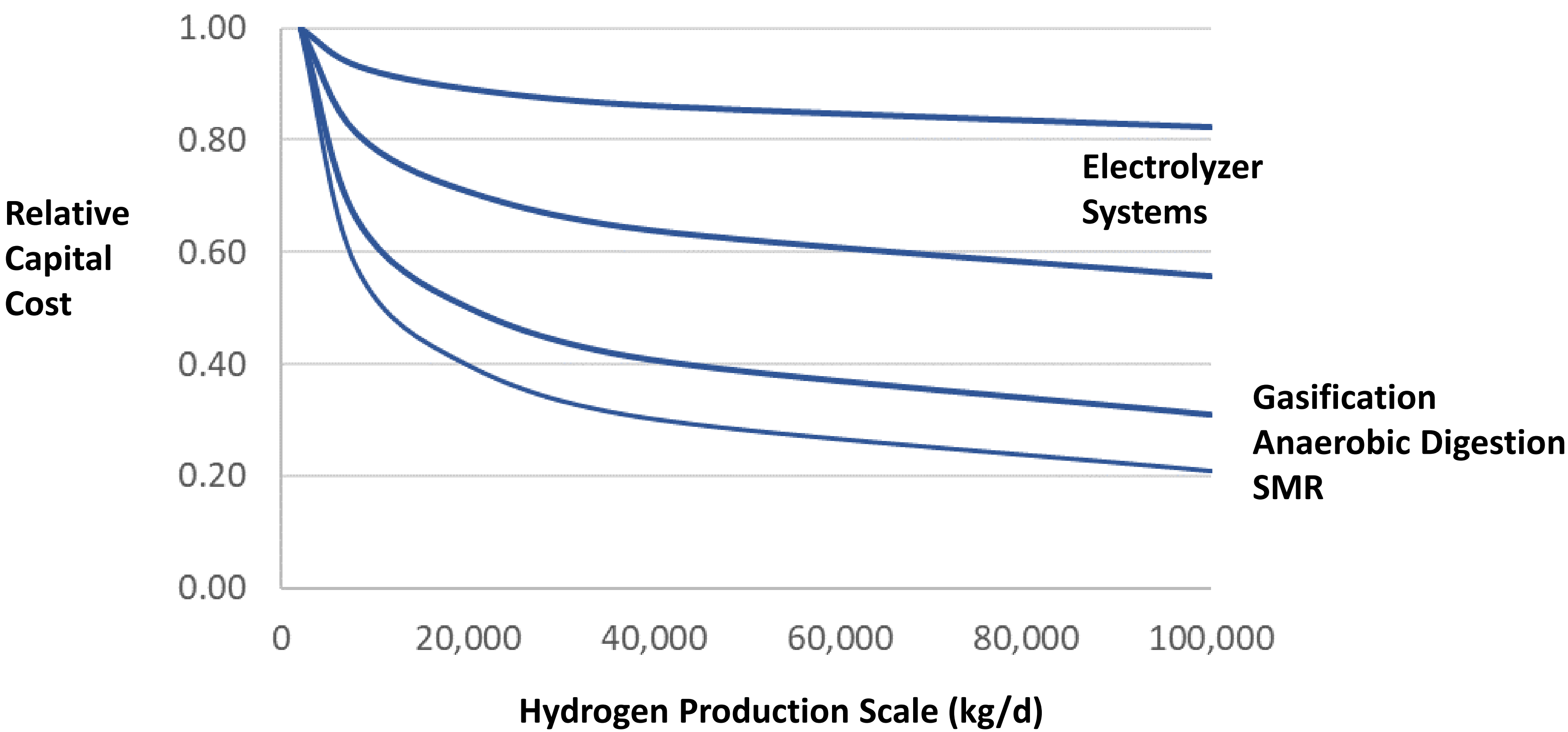


- **Adjusting cost estimates with different time stamps and currencies requires currency conversion and escalation**
- **These conversions can introduce additional uncertainty at times when the indices are changing rapidly but applying these adjustments generally reduces the spread in the data**

1 Refinery cost escalation index

2 Chemical Engineering Plant Cost Index

Scale Dependence of Unit Cost

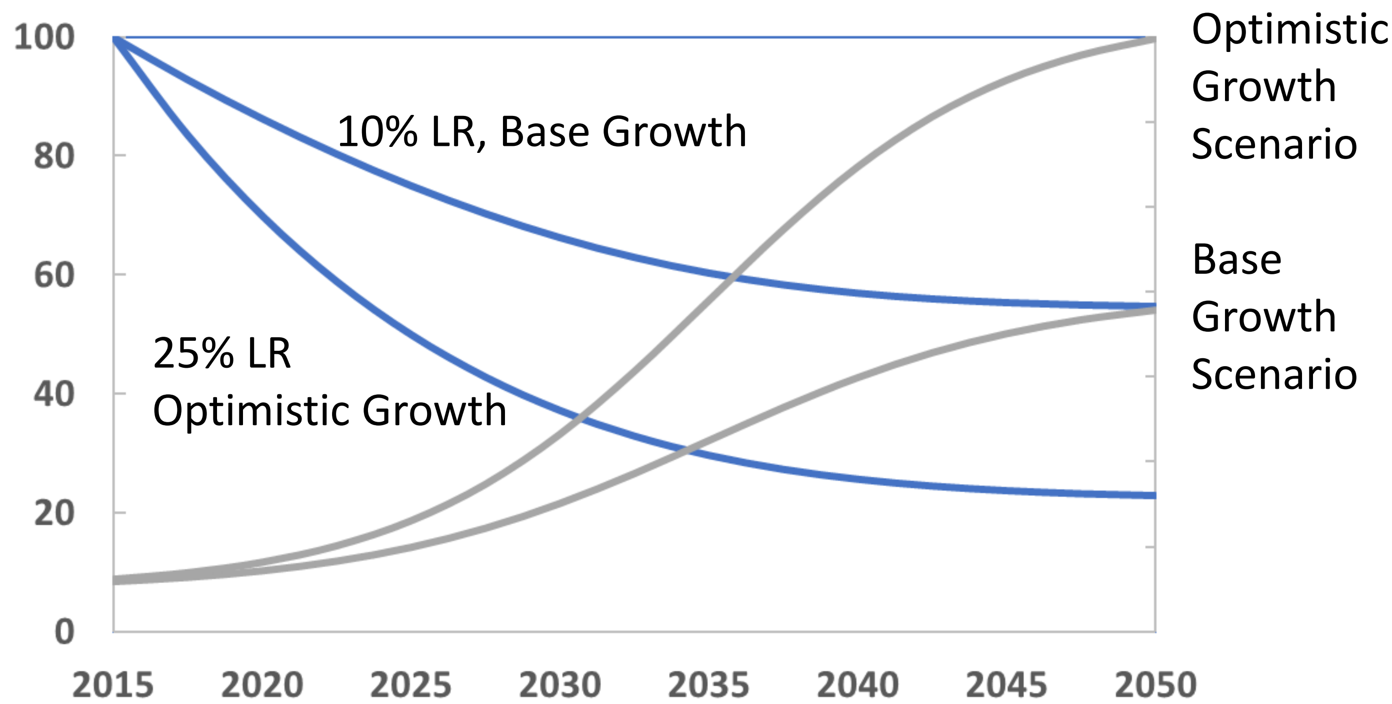


- **Electrolyzers show modest scale sensitivity while anaerobic digestion systems and gasifiers are highly scale sensitive and require scale of greater than 20,000 kg/day of hydrogen production capacity to reach minimum efficient scale**

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
- Literature and reports of all three types were used for this study
- Dollars normalized to $2018 using Consumer Price Index and/or Chemical Engineering Plant Cost Index (CEPCI)

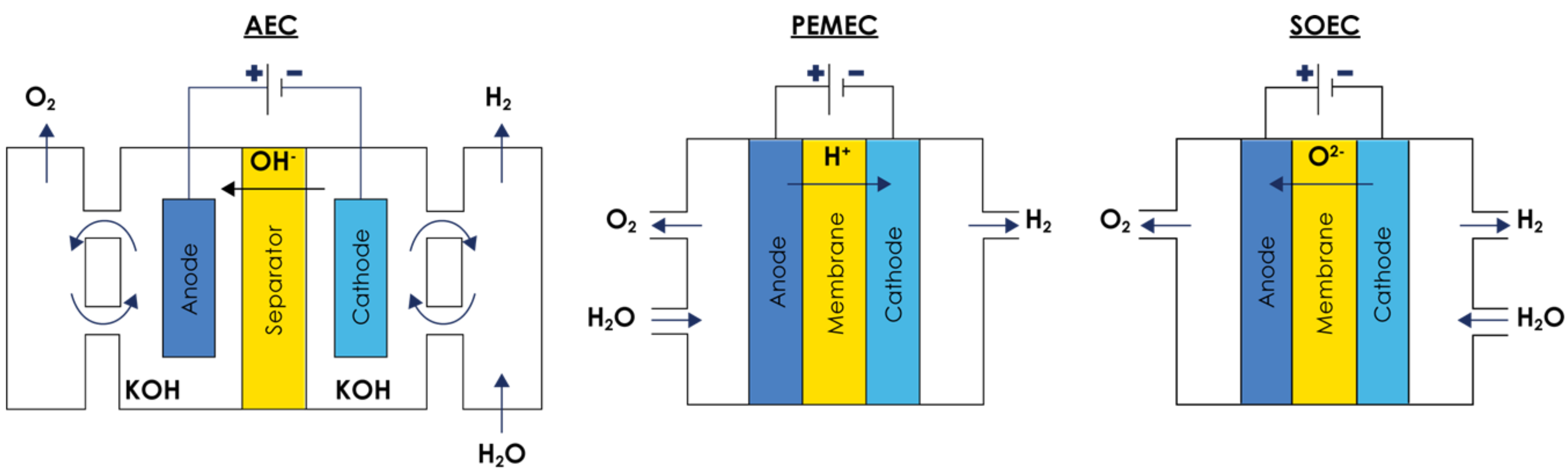
Market Growth and Learning Rate



- **Progress or learning rate has proven to be an accurate predictor or cost reduction for many technologies**
- **This group of methods 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**

Water Electrolysis

- **Water electrolysis creates hydrogen by splitting water into hydrogen and oxygen by applying voltage across an electrolyte**
- **There are several electrolysis technologies under development featuring different electrolytes and operating temperatures**

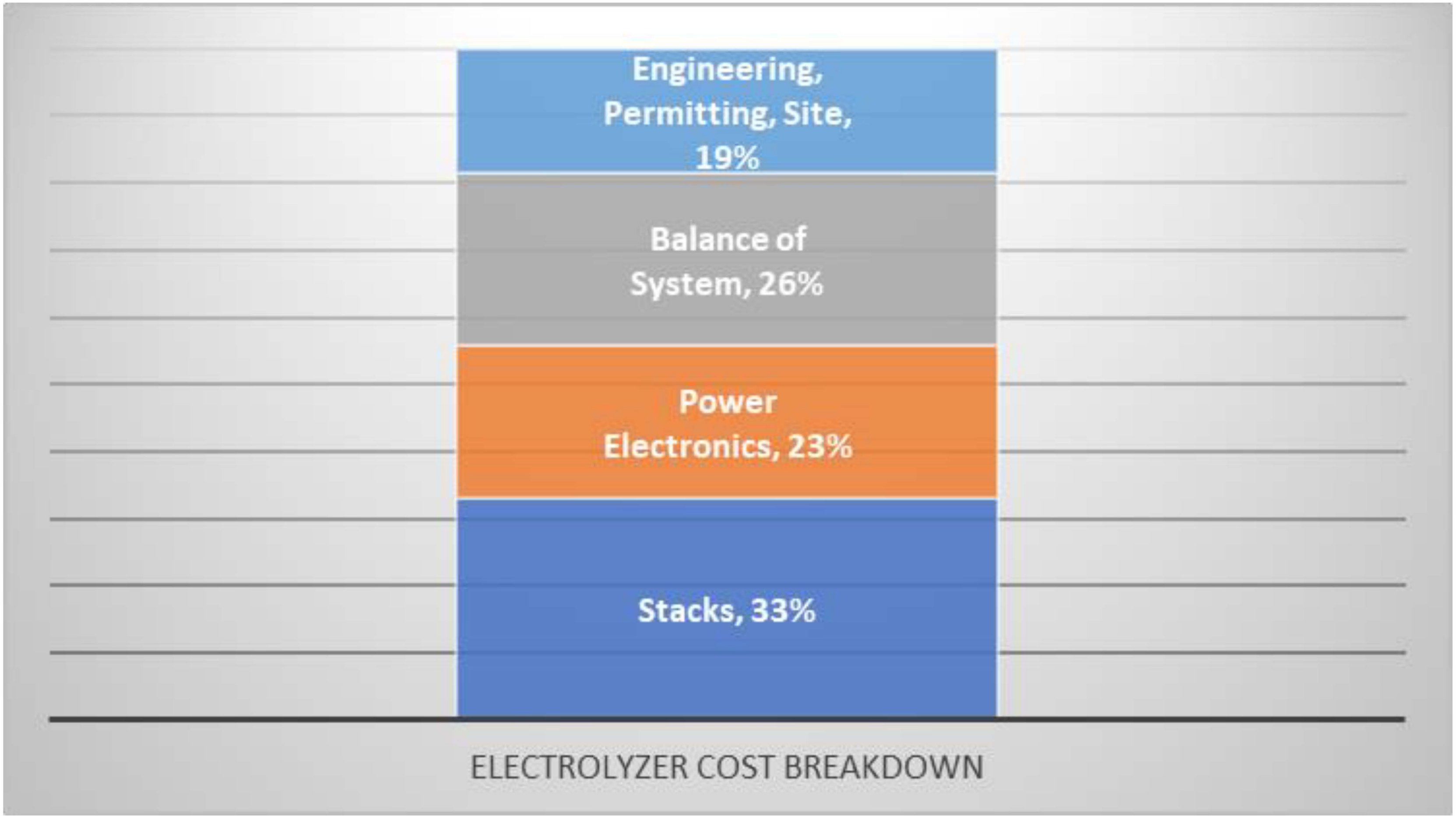


Operating Temperature	60 – 80C	50 – 80C	650 – 1000C

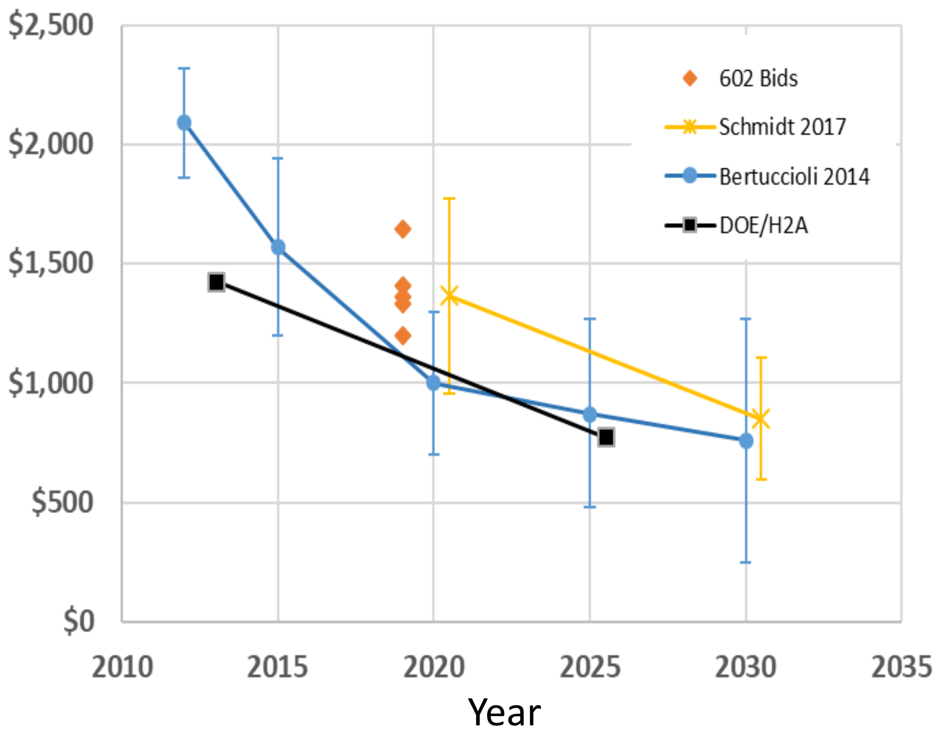
Electrolyzer Technical Maturity and Deployment Status

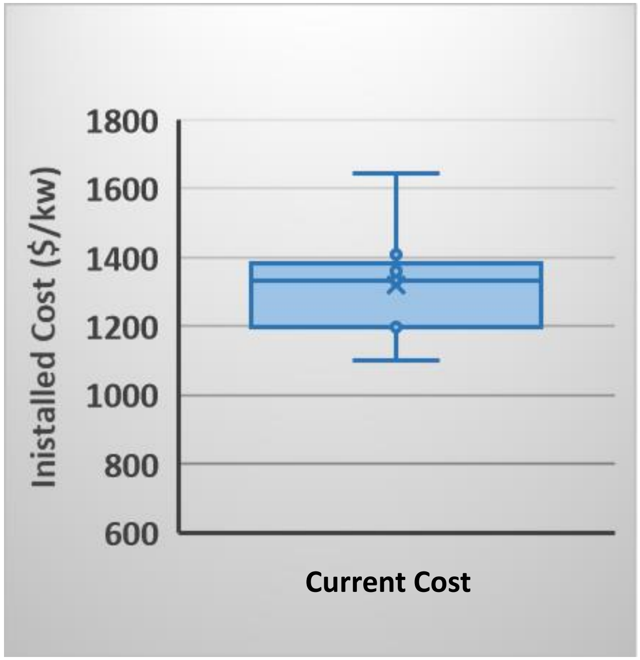
- Alkaline electrolyzers have been in commercial deployment since the 1960's and are commercially mature and have a global cumulative capacity base of 25 GWe
- PEM electrolyzers have been in commercial deployment for roughly 10 years and have a global cumulative capacity base of around 1 GWe
- Solid oxide electrolyzers are in pre-commercial development and expected to reach commercial readiness in the early 2020's

Typical Electrolyzer Total Project Cost Breakdown



PEM Electrolyzer Cost

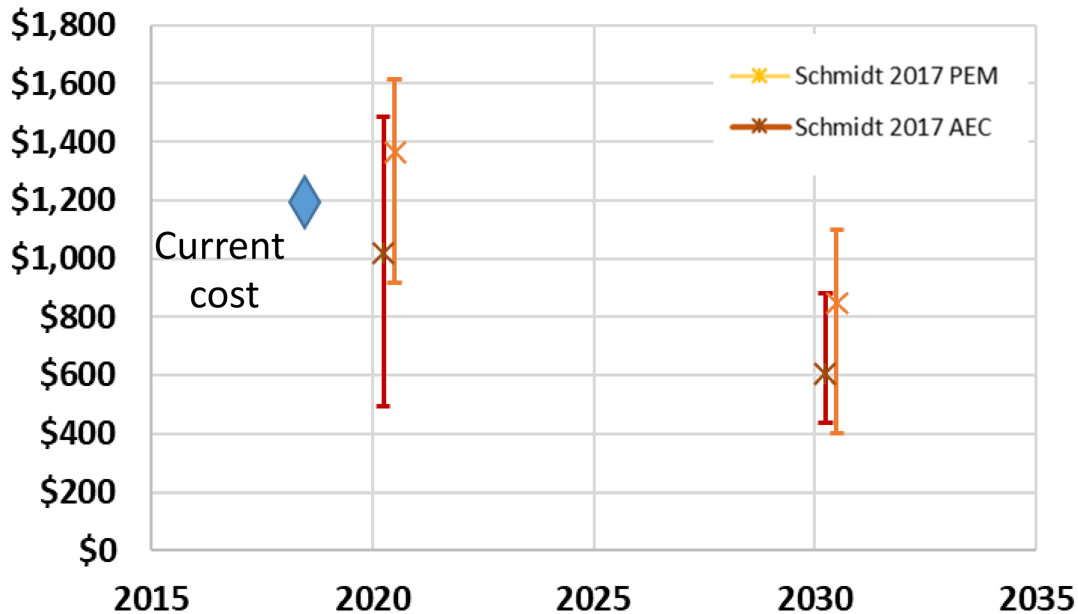




- The data from the GFO-17-602 bids are slightly higher than the other data sources but within range of the published data – the source could be price versus cost, early market added costs or inclusion of some indirect costs
- For purposes of this study, the average of the reported costs is used as the current cost basis ($1335/kW$_e$ installed)

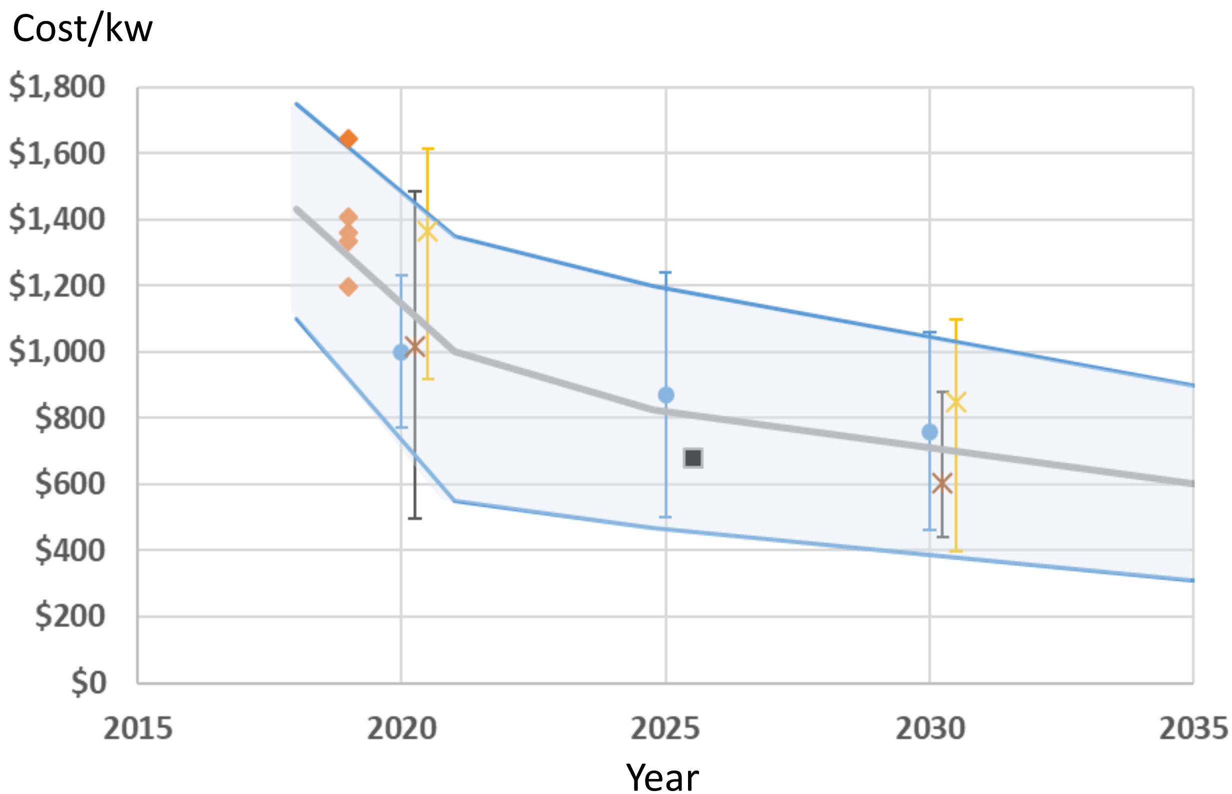
Scope: All-in installed cost excluding land, contingency and construction financing

Alkaline Electrolyzer Costs



- **Alkaline electrolyzer costs are estimated to be 20% to 40% below PEM costs but PEM costs are declining more rapidly to costs are expected to converge over time**

Electrolyzer Cost Forecast



- The various data sources are relatively consistent in their assessment of the rate of cost reduction although there is spread in the forecast costs at each time point
- High, Base and Low cost ranges have been established to capture the range of the forecast data
- Solid oxide electrolyzers are expected to enter the mix in the early 2020's – costs are expected to be within the forecast envelop

Current and 2030 Forecast Electrolyzer Performance Data

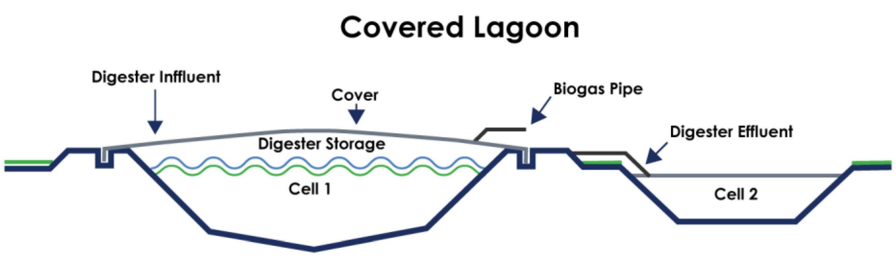
Parameter	2018 Value	2030 Value
Stack Electricity Use	49.2	46.7
Total System Electricity Use	54.6	50.2
Stack Life	60,000 hours	85,000 hours
Fixed Maintenance O&M	3 – 3.2% of Capex	Pro-rate with Capex

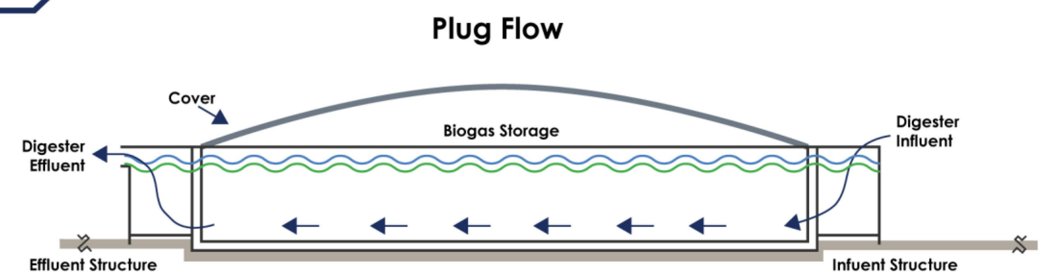
- **The above values are taken from the DOE current and future H2A Case studies for PEM electrolysis**
- **Values are consistent with the forecasts in Schmidt and Bertuccioli**

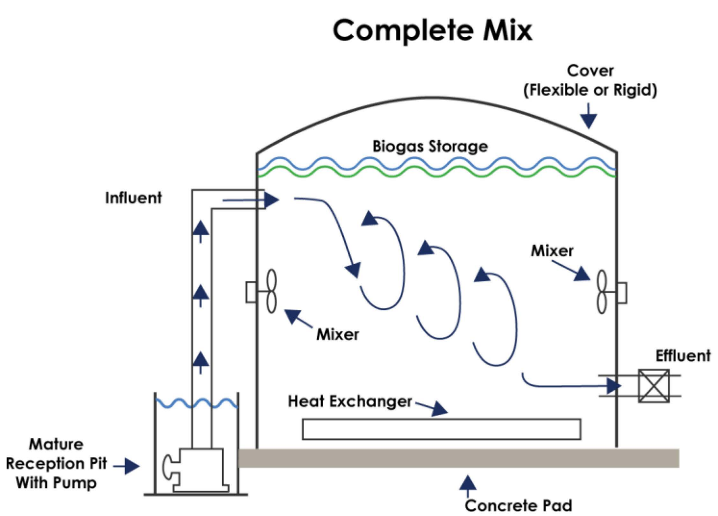
Anaerobic Digestion

- Anaerobic digestion is the decomposition of organic matter in an oxygen-free environment
  - The primary products are methane and CO_2
  - Feedstocks include animal waste, food waste, sewage, green waste and other materials
  - Anaerobic digestion is suitable for biogenic feedstock with relatively high moisture content
- Product gas requires CO_2 separation and other conditioning steps if is to be pipeline injected or used as vehicle fuel
- Renewable hydrogen pathways require reformation of the product methane into hydrogen

There are a variety of AD technologies

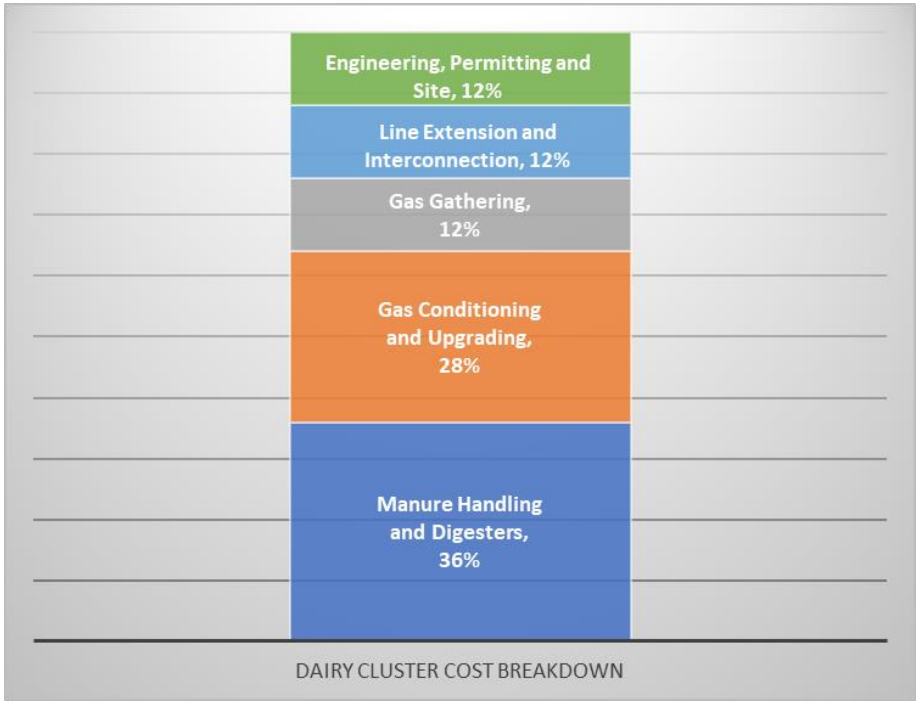




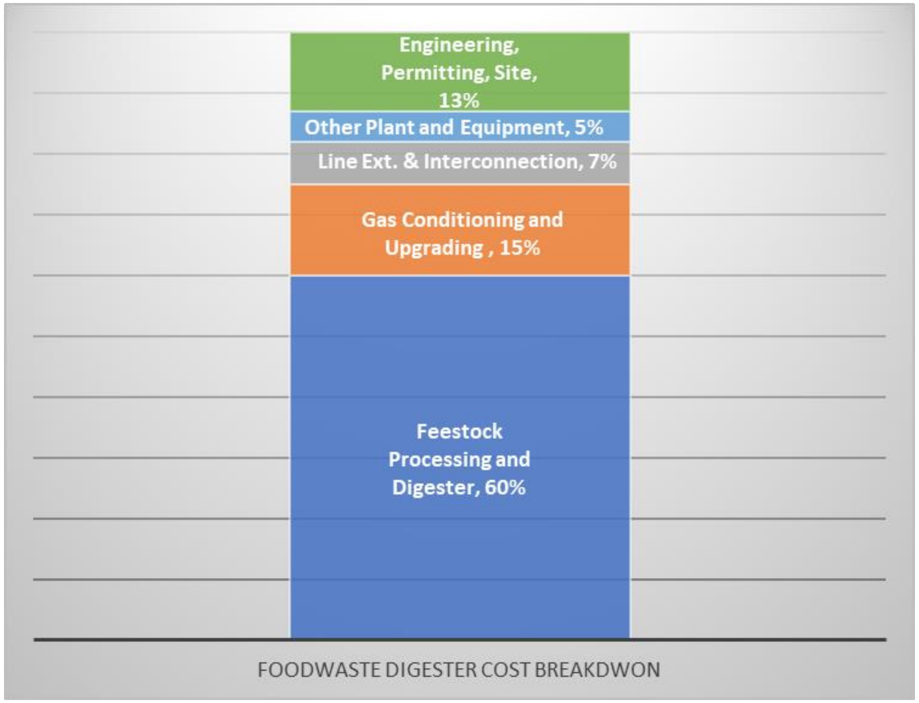


Representative Cost Breakdowns

$100 - $200/(MMBTU/yr)

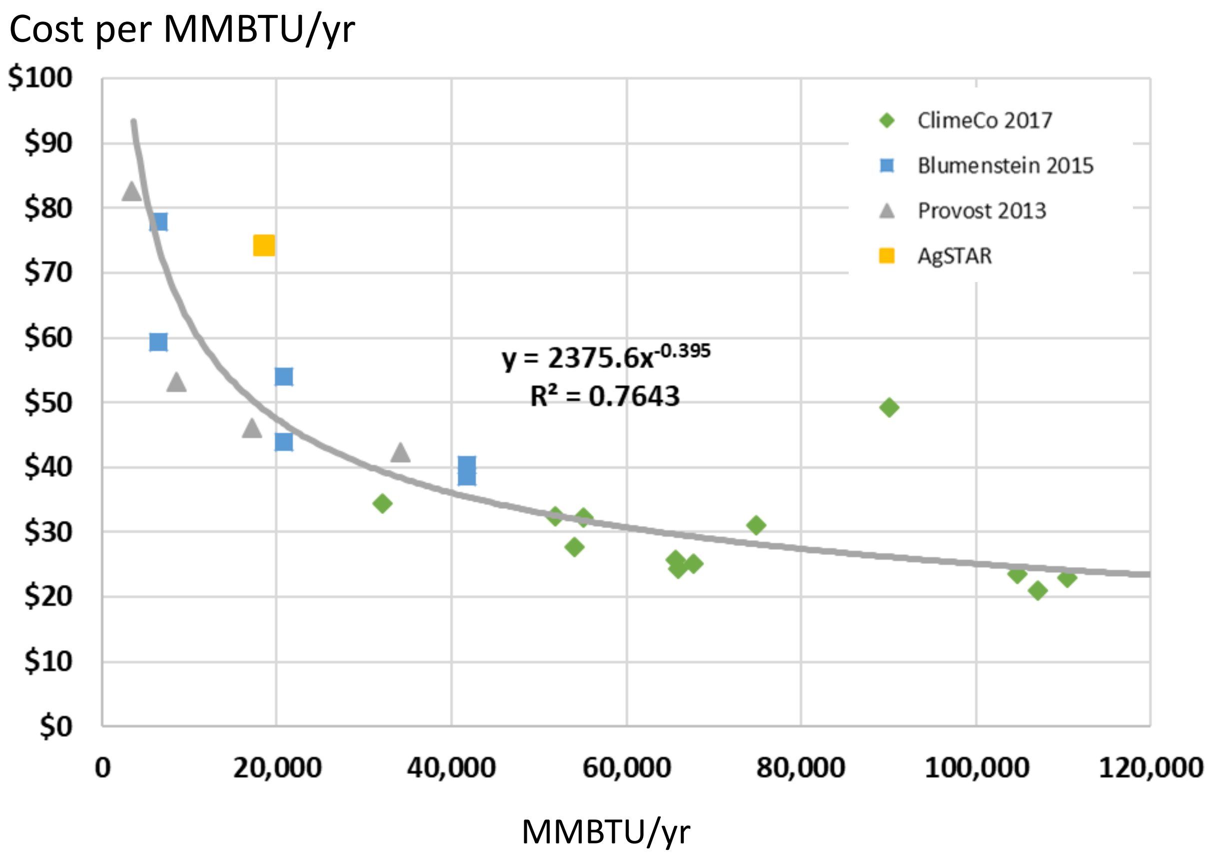


$200 - $300/(MMBTU/yr)



Scope: Total project cost excluding contingency, land purchase and construction financing

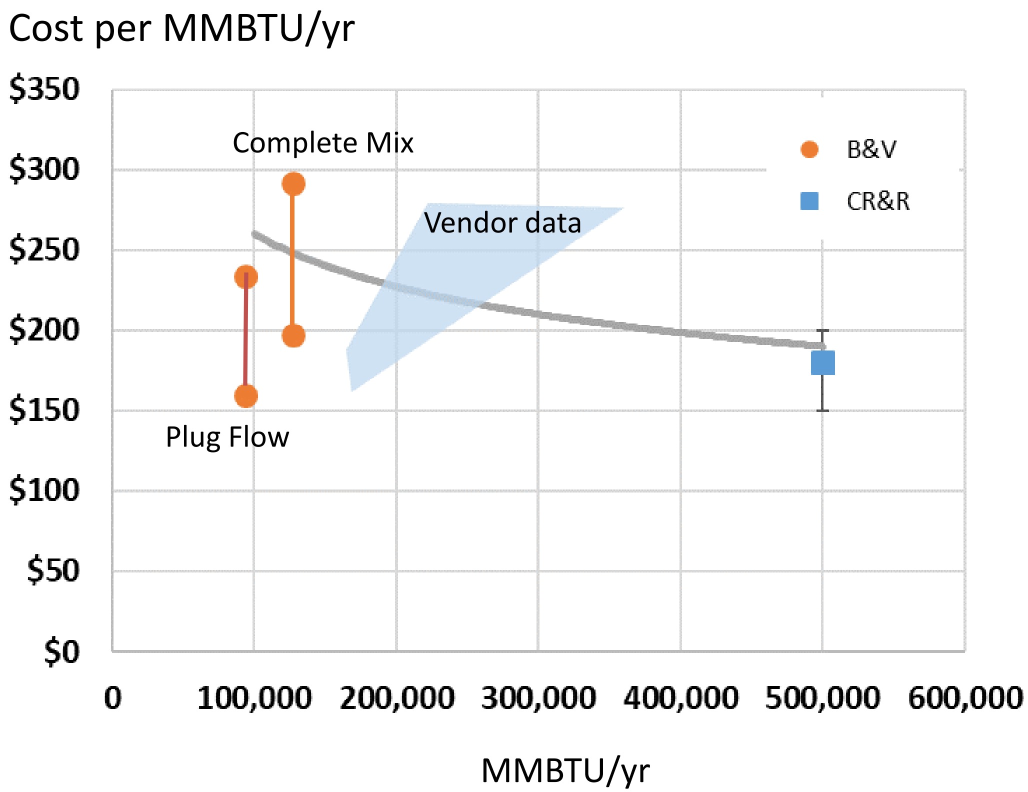
Double Lined Covered Lagoon Dairy Digester Costs



- Scope: Double-lined covered lagoon and manure handling
- Data correlation is very good with the exception of two outliers
- Uncertainty band of +/- 20% captures nearly all the data

Scope: digester system, manure handling, peripherals

Complete Mix Digester Costs



- **Less data available on complete mix systems but, for the scope considered, costs are in the range of $225 +/- 25% over the size range considered**
- **Additional data gathering is on progress**

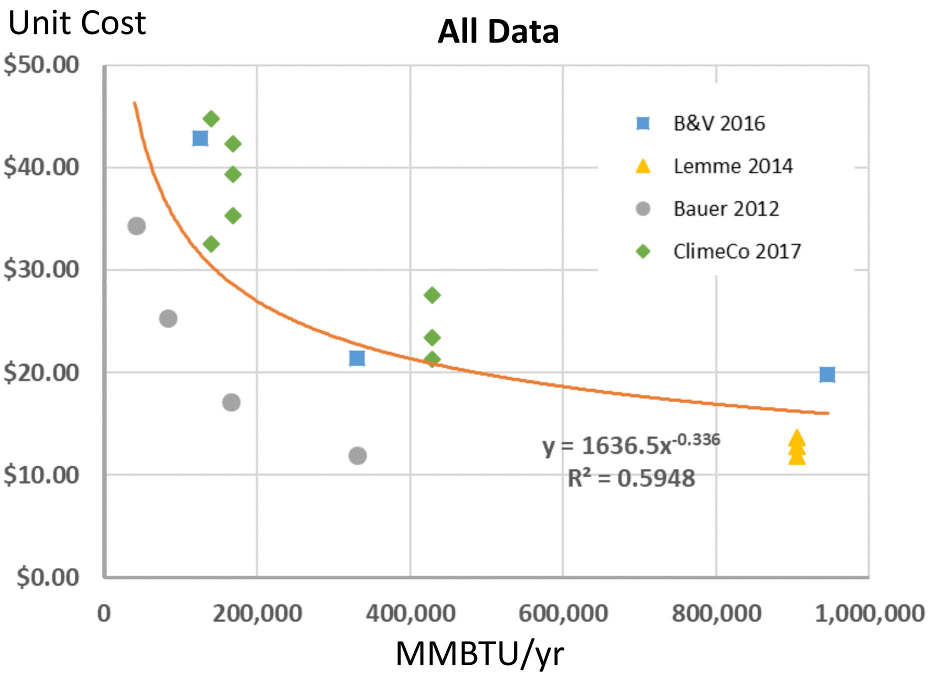
Scope: All-in installed cost excluding construction financing

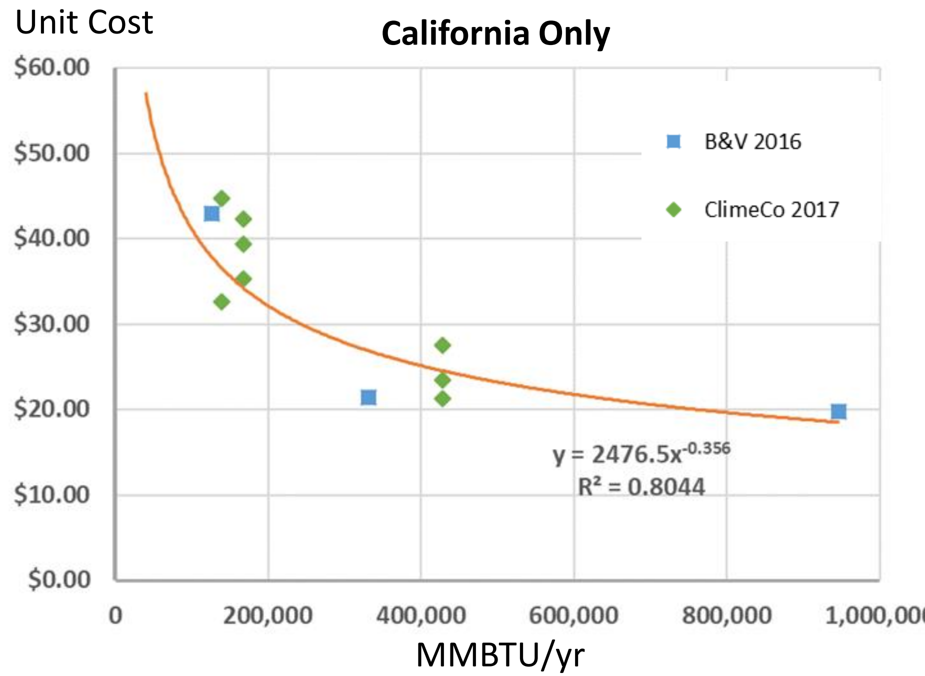
Biogas Conditioning and Upgrading

- Biomethane projects have employed a variety of gas upgrading technologies
  - Pressure Swing Adsorption
  - Membranes
  - Amine Scrubbers
  - Water Scrubbers
  - Cryo separation (not fully commercial)

- There is project-to-project variation in cost based on raw biogas composition
  - Methane fraction
  - Presence of sulfur, nitrogen, siloxanes and other constituents

Conditioning and Upgrading Costs





- **Data consistency is relatively good with the various technologies grouping within +/- 10%**
- **Scale factor approximately 0.65**
- **California-only data shows a high degree of consistency (correlation)**

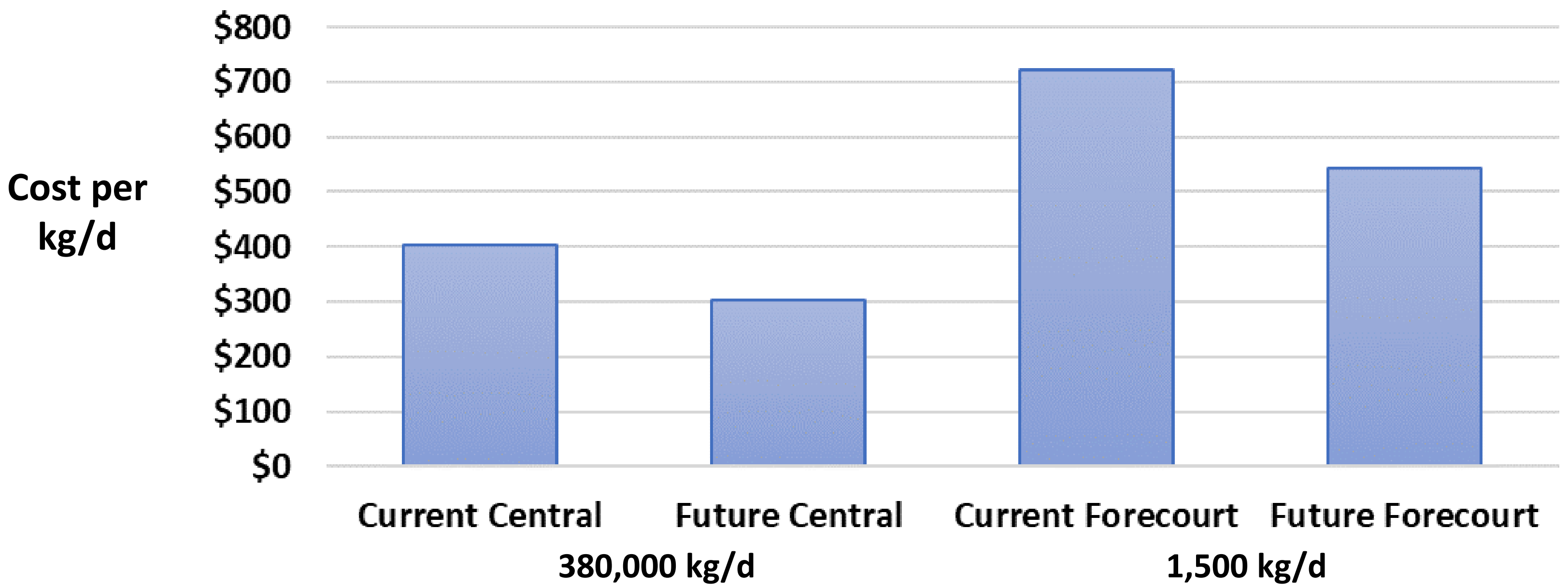
Methane Reformation

- The pathways that yield methane or a high methane fraction require reformation
- Steam Methane Reformation is the most widely used process

  $$\text{Heat} + CH_4 + 2H_2O = 4H_2 + CO_2 \text{ (SMR Reaction)}$$

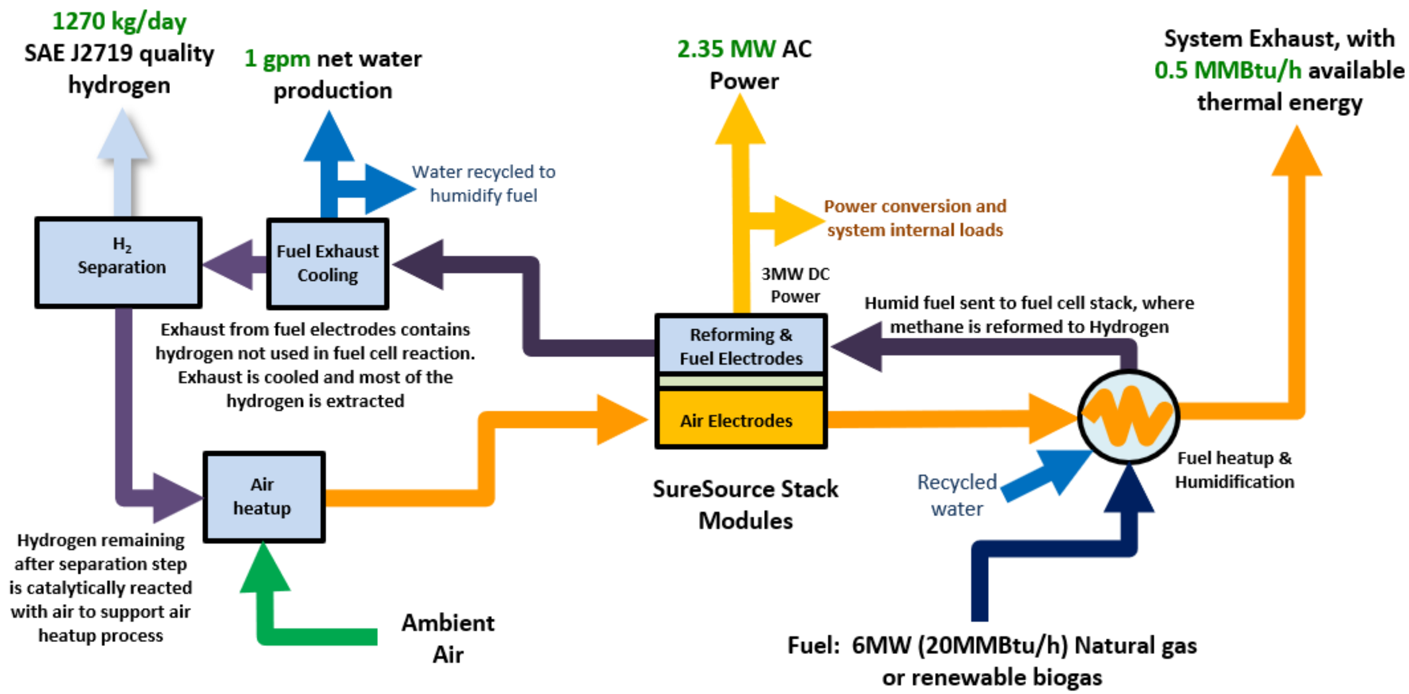
- Other concepts are being pursued
  - Dry reforming
  - Partial oxidation / chemical looping
  - Autothermal
  - Catalyst, plasma-stimulated and other concepts
- Reducing cost at small production scale (2,000 kg/d) is an important research focus

Reformer Cost forecast



- **DOE H2A model predicts 25% capital cost reduction over a 10-year horizon**
- **Further literature review planned**

Tri-generation



- Tri-generation is a concept in which fuel cell systems using RNG as the primary fuel produce electricity, hydrogen and heat
- Project at POLB employing this concept under development
- Techno-economic assessment in progress
- Electricity revenue is key to net hydrogen production cost

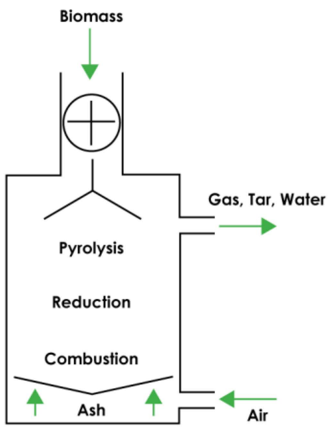
Reformed Biomethane Cost Reduction Potential

- Additional assessment needed (e.g. time series data on cost digester costs in Europe)
- Like other RH2 technologies, scaling the supply chain will contribute to lower costs
- Soft costs and contingencies will benefit from repeat effect
- Expect a 5% to 10% learning rate by analogy with other technologies

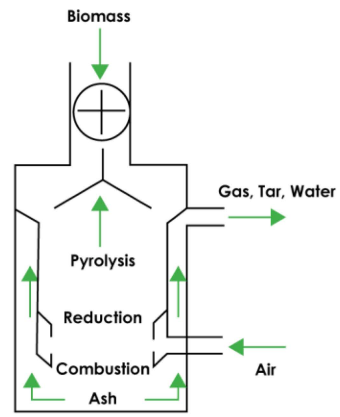
Thermochemical Conversion

- There are several types of processes for creating hydrogen from organic feedstock including
  - Gasification
  - Pyrolysis
  - Hydrothermal processing
- All of these processes use heat to evolve the volatile hydrocarbons from biomass to create syngas which is further to create hydrogen, methane or liquids
- The cost and performance assessment focuses on gasification as a proxy for this group

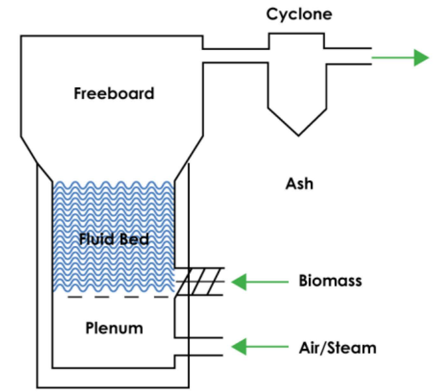
Gasifier Types



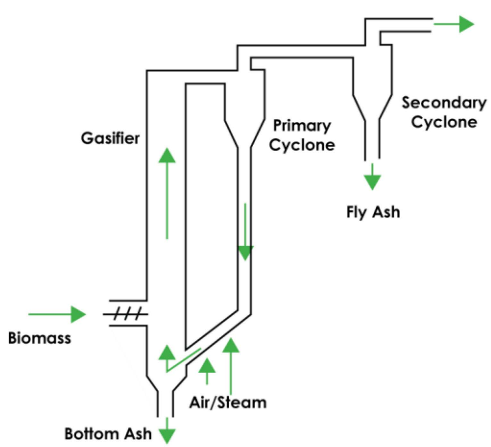
Updraft Gasifier



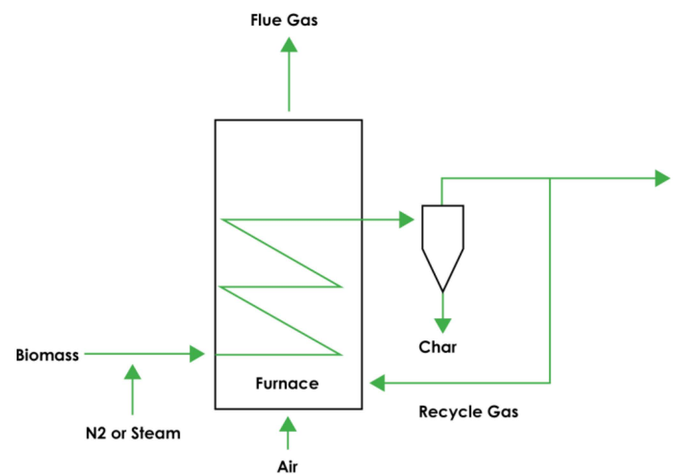
Downdraft Gasifier



Fluid-Bed Gasifier

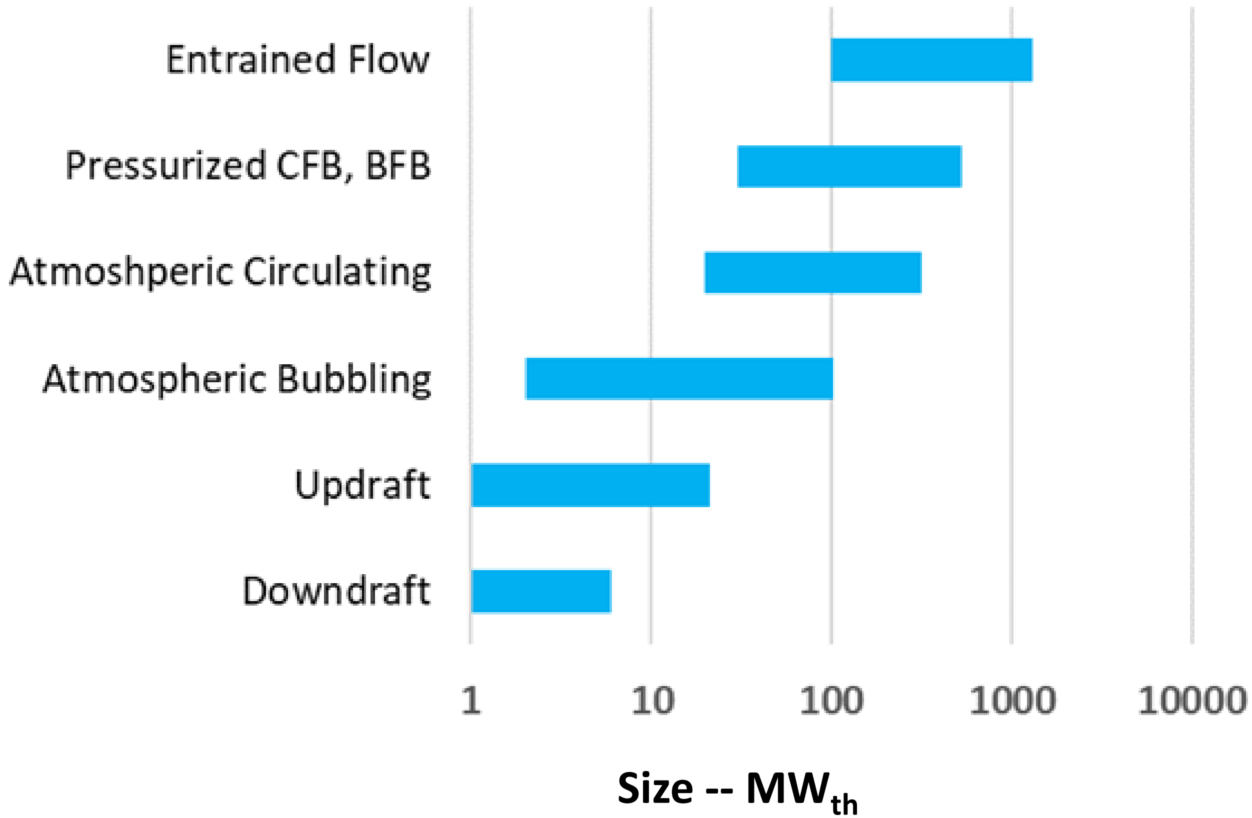


Circulating Fluid-Bed Gasifier



Entrained Flow Gasifier

Size Range by Gasifier Type

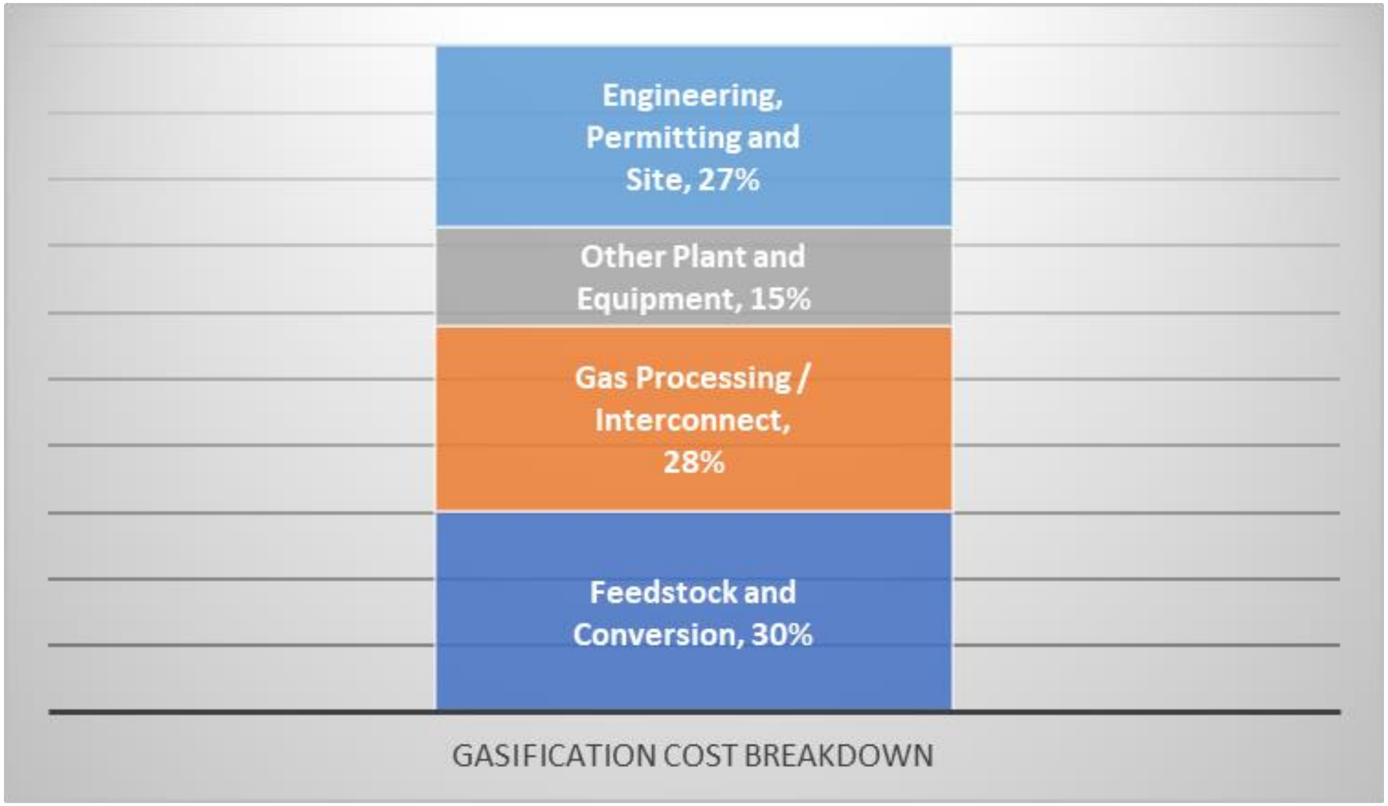


Interim Results

Gasifier Technical Maturity and Deployment Status

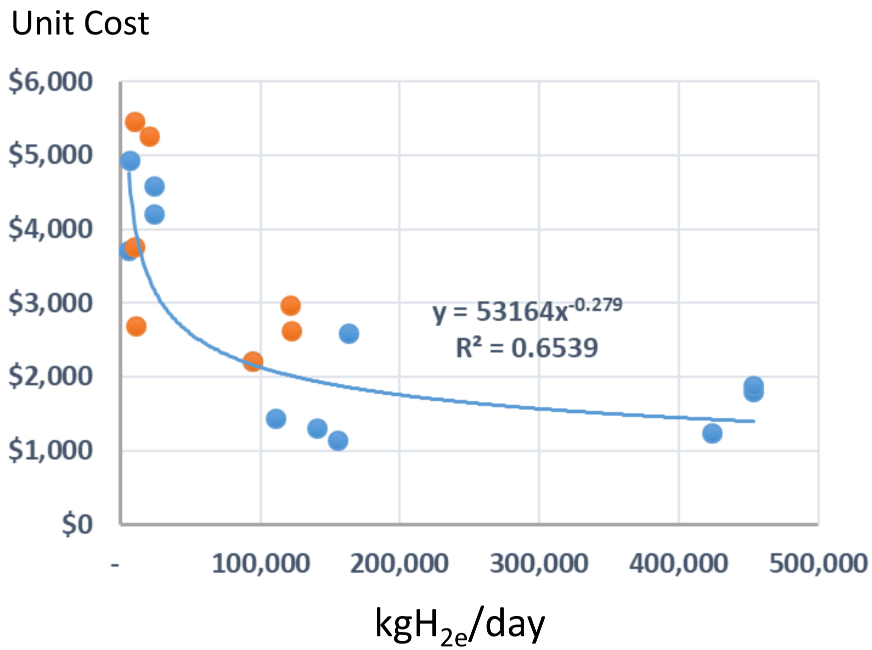
- Gasification technology has been in development since the 1960's, primarily for coal gasification
- Biomass gasification has been under development since the 1980's
  - Most projects have used biomass as a blend-stock for coal gasifiers
  - Biomass-only gasification is at the pilot and early commercial stage
- Databases show 50 - 90 biomass gasification facilities worldwide with ~10 in California
  - Majority are sub megawatt and many are in CHP applications
  - No dominant technology

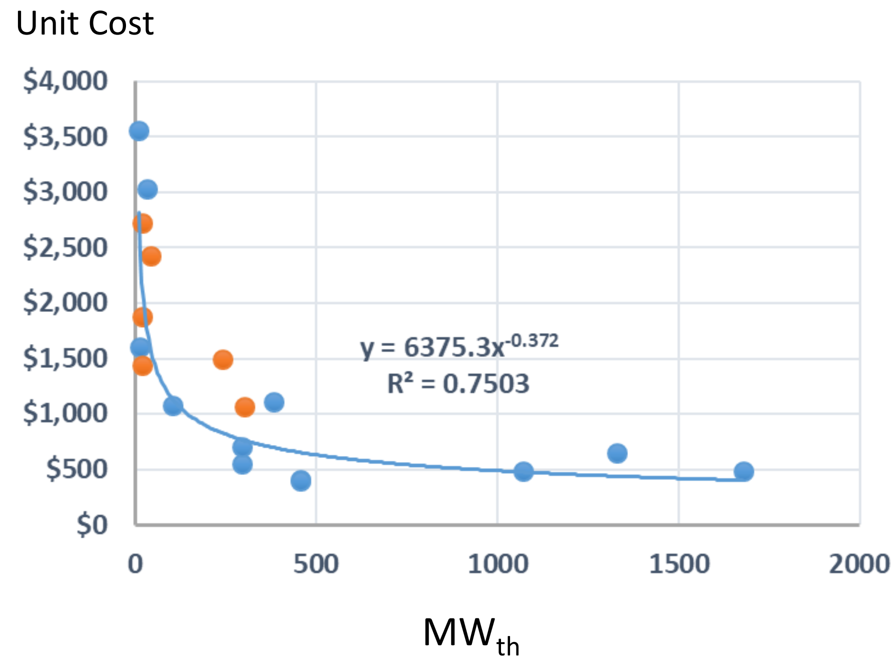
Typical Cost Breakdown for All-in Gasification Project



Costs exclude contingency, construction financing and land acquisition

Gasification System Costs – Current





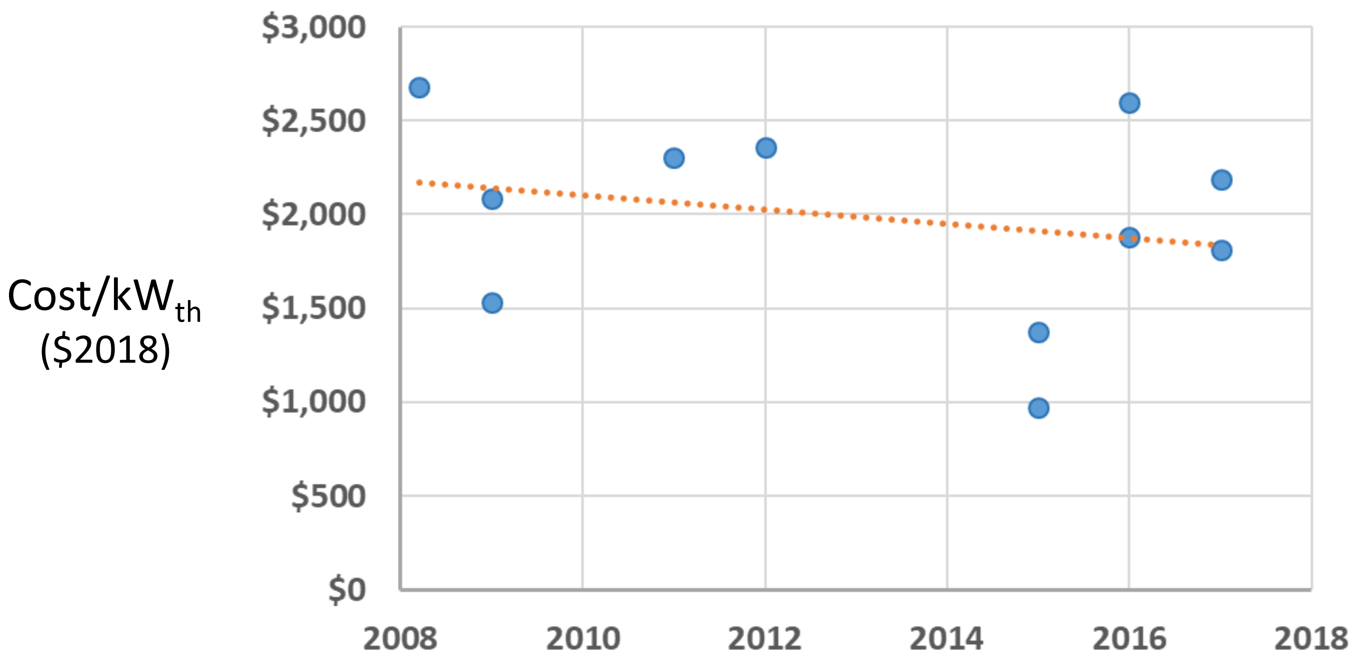
- **Total system cost can be normalized based on feedstock input quantity (MWth) or on product volume – the correlation is slightly better based on input**
- **The scale factor is between 0.63 and 0.72 based on the data used here – this is consistent with values reported in the literature and shows that plant size of around 100 MTH2/day (~300 MWth) is the minimum efficient scale**

Scope: complete system exclusive of construction financing costs and contingency

Gasification Cost Forecast

- Literature on future cost improvement potential for gasification systems is limited
- H2A "future case" shows a 7% improvement in cost based on a specific set of design improvements to the circulating bed technology (1 technology generation)
- A 2004 study by the National Academy of Science estimated a 50% capital cost reduction potential for a 24,000 kg/d facility from early unit to fully learned out
- Other studies identify potential improvements leading to a 50% cost reduction assuming that all the identified innovations and improvements are successful (not likely)
- Neither coal nor biogas gasification projects show a statistically significant learning-rate correlation to date – but, in the case of biomass, the installed base is very low so significant learning effect would not be expected
- If biomass systems were to exhibit a learning rate of 10% (using GTCC as a proxy) and 15% annual growth in installations beginning in 2020 they would achieve cost reduction of roughly 20% by 2030
- For purposes of this study, an improvement in cost of 10% to 30% with a base case of 20% will be used from current costs through 2030 following a typical progress curve shape

Biomass Gasification Cost Progression



- **The trendline for normalized gasification cost shows 2% year decline but the tend is not statistically significant**
- **Indicative of the low rate of system additions to date yielding little learning effect**

Current and 2030 Forecast Gasification Performance Data

Parameter	2018 Value	2030 Value
Gasification Efficiency	65%-70%	5% relative improvement
Total System Efficiency	50%	5% relative improvement
Fixed Maintenance O&M	5% of Capex	Pro-rata with Capex

- **The above values are taken from the DOE current and future H2A Case studies for gasification**

Plant Gate to Customer

- **Utilize H_2 Delivery and Scenario Analysis Model (HDSAM)**
  - **Resolves terminal, transport, and refueling station costs**

Main inputs:

- Population of area served
- Area served
- Vehicles/person
- Miles driven/vehicle/yr
- H2 market type: urban, rural interstate, combined
- Transport mode
- H2 vehicle market %
- HRS capacity
- Production volume estimates: low, mid, high

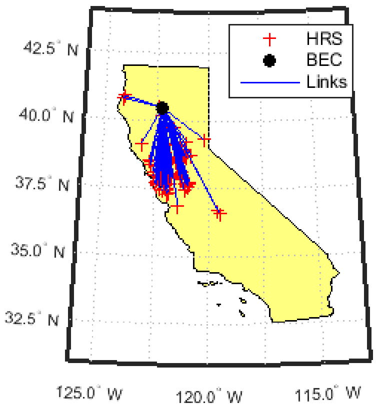
Estimate based on population that can be served from a given production facility

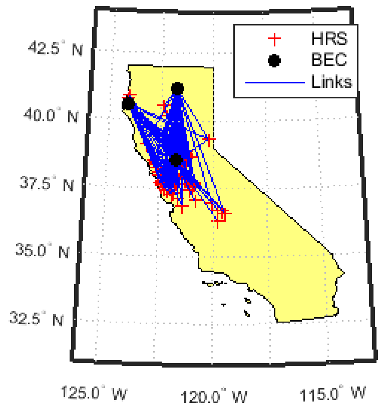
Default

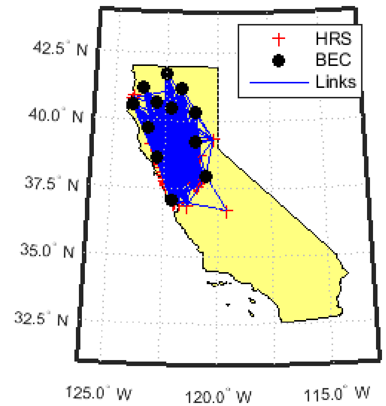
Liquid Truck

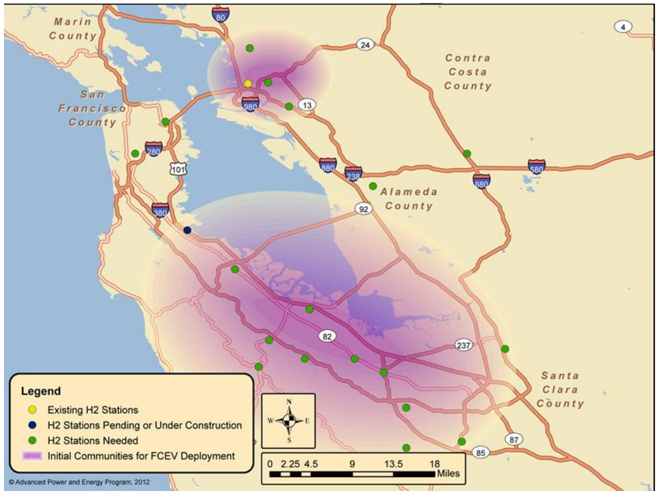
Plant Gate to Customer

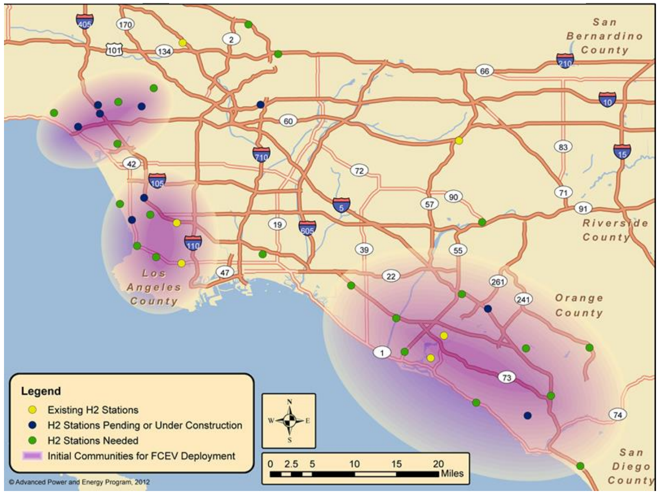
- **Area served and Population**
  - **Calculate areas and population using GIS tools and LandScan data**





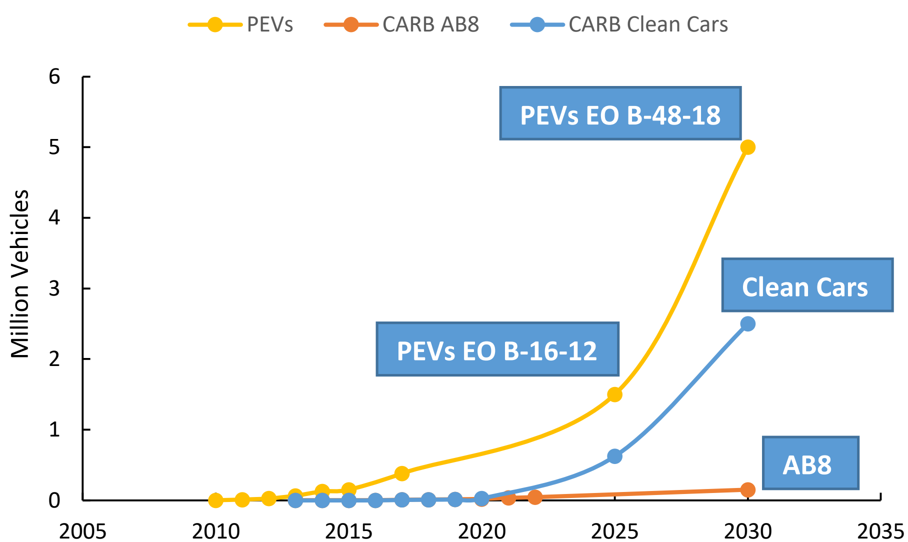




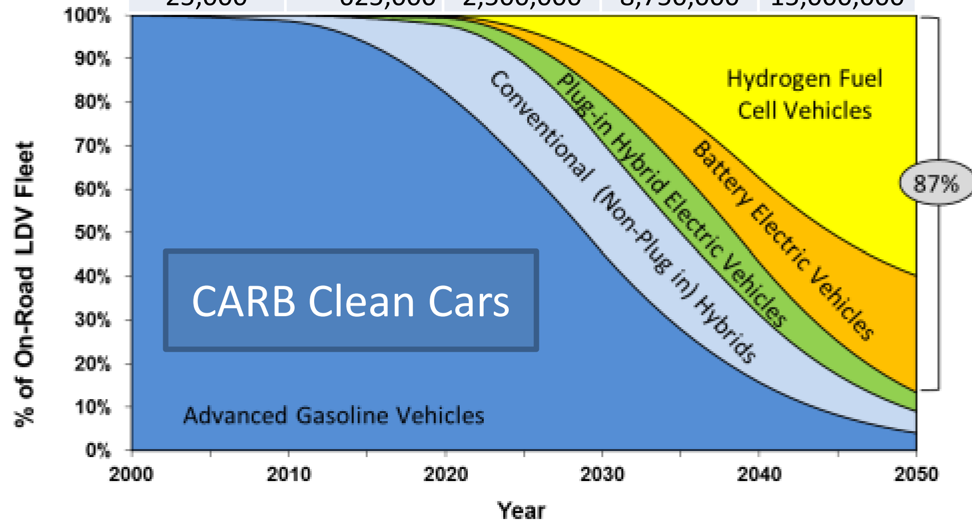


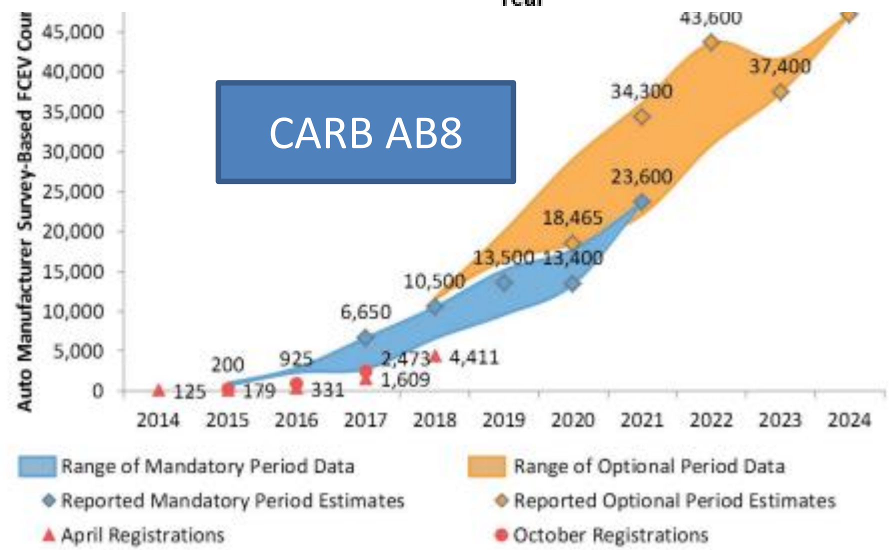
Plant Gate to Customer

- **H2 vehicle market %**
  - **Align projection with statewide goals**



2020	2025	2030	2040	2050
0.10%	2.50%	10%	35%	60%
25,000	625,000	2,500,000	8,750,000	15,000,000





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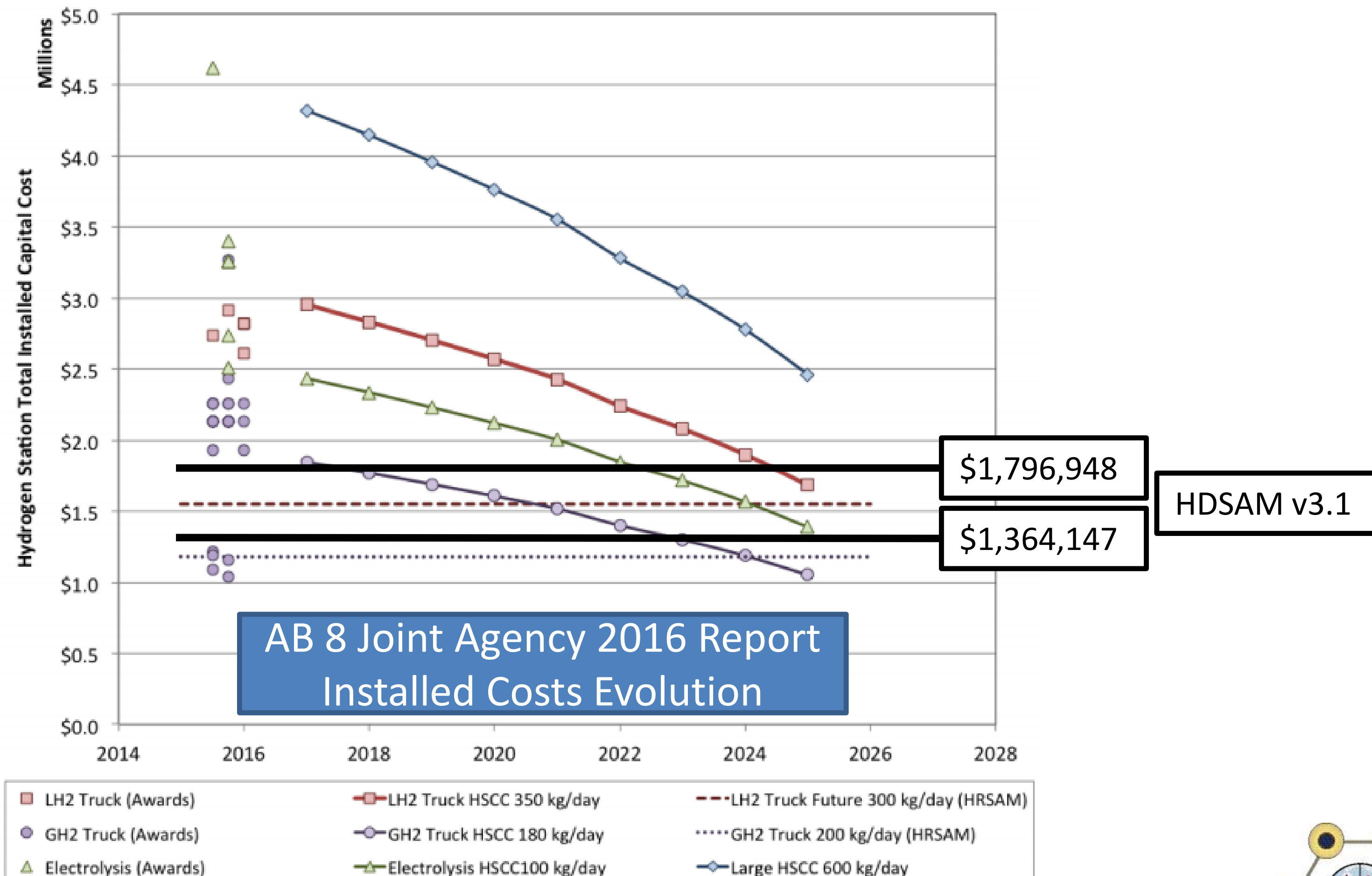
Plant Gate to Customer

- **HRS Capacity**
  - **1000 kg/d: 2020-2025**
  - **2000 kg/d: 2025-2030**
- **Production volume estimates**
  - **Mid: 2020-2025**
  - **High: 2025-2030**

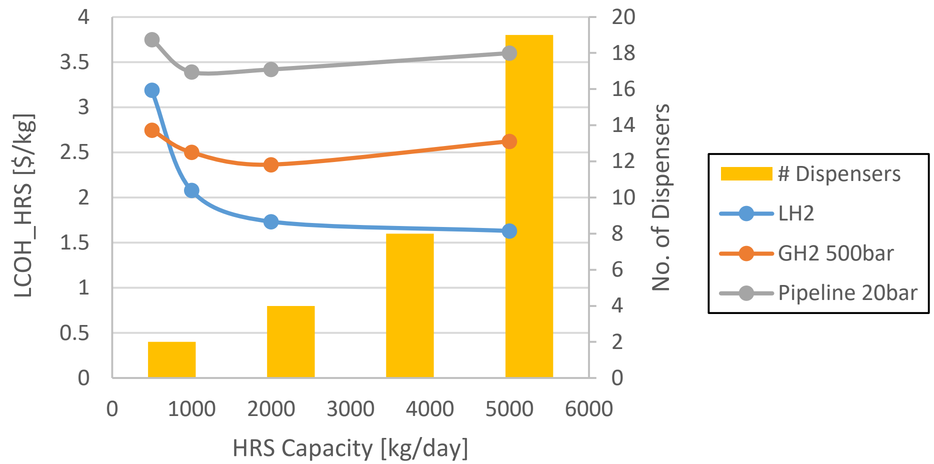
Plant Gate to Customer

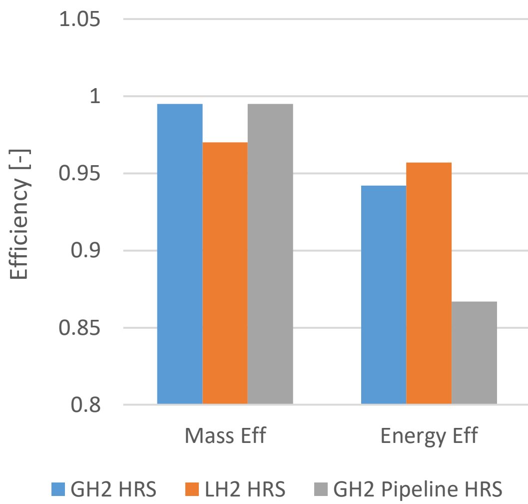
- **HRS Installed Cost Evolution**
  - **Use numbers from AB 8 Joint Agency Report 2016**

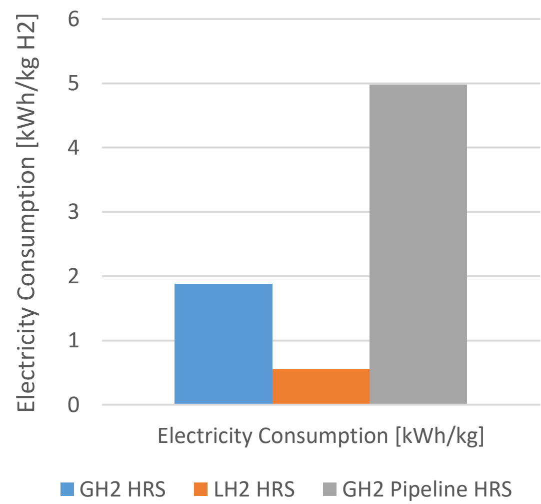


Plant Gate to Customer

- **Sample Output for HRS costs**







Interim Results

Further Steps in Roadmap Development

Task 2

Technology Cost and Performance

- Reports and academic research
- Bid documents / Developer input

Feedstock Cost and Availability

- Published studies (e.g. Davis, BT2)
- H_2/CH_4 allocation scenarios
- Electricity costs from RESOLVE

Siting Constraints

- Footprint and emissions
- Zoning
- Access to feedstock and infrastructure and demand points
- DAC screen

Renewable Hydrogen Demand Evolution

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

Task 3

Siting Analysis -- Production and Delivery Chain Options

- Candidate sites by technology and grid location
- ArcGIS geospatial model layers and supply / demand heat maps

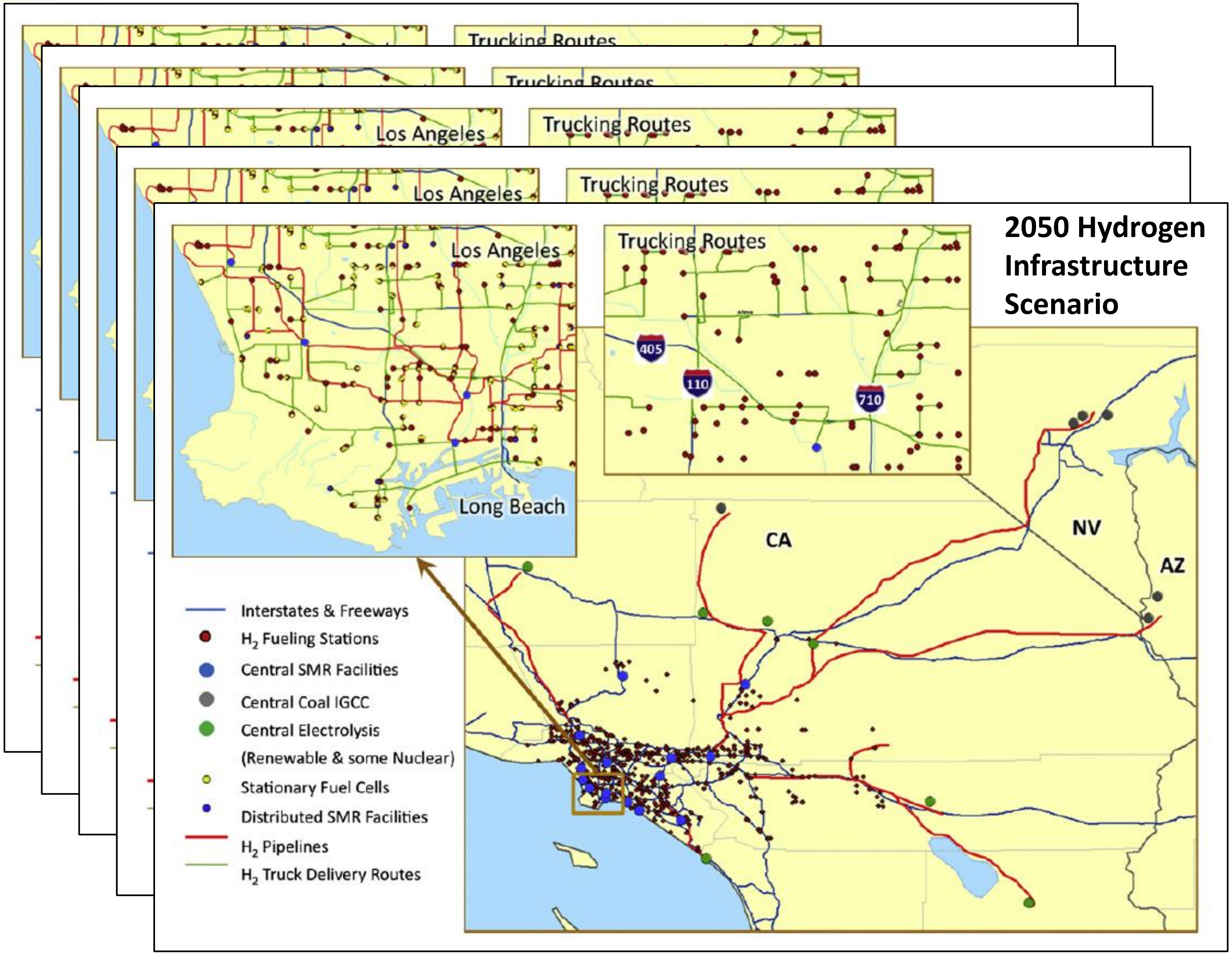
Task 4

Integrated Renewable Hydrogen Roadmap

- Spatial and temporal build-out scenarios (starting from existing and planned projects)
- High-level optimization and build sequencing
- Aggregate investment and RH2 cost projections
- Barriers and enabler and policy needs
- Future research needs

Task 1: Agreement Management (Reporting and Deliverables)

Time-Phased Renewable Hydrogen Deployment



Source: Projecting full build-out environmental impacts and roll-out strategies associated with viable hydrogen fueling infrastructure strategies. Stephens-Romero S.; Brown, T.; Carreras-Sospedra, M.; Kang, J.; Brouwer J.; Dabdub, D.; Recker, w.; Samuelsen, G. S.; Int'l Journal of Hydrogen Energy, 2011

Interim Results

Some Key Products as the Work Proceeds

- Complete reference specification by technology and size including plant exist conditions for plant-gate $/kg calcs
- Feedstock, siting and market analysis
- Aggregate investment requirements over time
- Progression of cost of dispensed hydrogen over time
- Carbon credit values needed for break even over time (LCFS, RIN and other)
- Policy recommendations
- Points of highest leverage for RD&D

Questions?

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