Analysis of Hydrogen in California for Senate Bill 1075 Report

California Air Resources Board

Public Workshop Materials

February 25, 2025

Energy+Environmental Economics

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Agenda

1) **Project Overview**
2) **Progress Update:** Methodologies and Initial Findings
   a) Hydrogen **P**roduction → **P**
   b) Hydrogen **T**ransmission **& D**istribution → **T&D**
   c) Hydrogen **E**nd-**U**se → **E-U**
3) **Summary of Key Questions for Public Comment**
4) **Appendix**

Project Overview

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Project Background: Senate Bill (SB) 1075

Report is mandated by State legislation

- **In 2023, the State of California approved the 2022 Scoping Plan Update (Plan) which lays out a cost-effective and technologically feasible path to achieving carbon neutrality by 2045 and reducing anthropogenic emissions by 85 percent below 1990 levels**
  - The Plan emphasizes employing all tools available to reduce greenhouse gas (GHG) emissions and remove carbon dioxide from the atmosphere to achieve carbon neutrality; this will require deployment of a broad portfolio of existing and emerging fossil fuel alternatives to achieve deep decarbonization across multiple sectors of the economy
- **SB 1075 (Skinner, Chapter 363, Statutes of 2022) requires the California Air Resources Board (CARB), in consultation with the California Energy Commission, California Public Utilities Commission, the California Workforce and Development Board, and other partner agencies, to produce a comprehensive report on hydrogen (Report)**
- **This Project is intended to provide technical, policy, and market analyses that will inform or be included in the Report directed by SB 1075**
  - This will include analyses that are responsive to the legislation by evaluating the role of hydrogen production, transmission, distribution, and end-use or storage in the California market

The Report must be comprehensive, comprehensible to non-technical audiences, and constructive in the support of informing public planning

The Project Team

A broad and deep team of experts is supporting CARB in preparing this Analysis

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Energy & Environmental Economics (E3)

- Energy consulting firm based in San Francisco, specializing in techno-economic analysis
- E3 helps policy makers, utilities, regulators, developers, and investors active in the energy industry make sound strategic decisions to navigate the energy transition
- Led evaluation of greenhouse gas reduction scenarios for CARB 2022 Scoping Plan update

Role: In addition to managing the project, E3 is leading the analysis, recommendations, and writing of the final Analysis

Prime Contractor

Black & Veatch (B&V)

- Leading engineering, construction, and consulting firm
- Industry leader in green hydrogen projects, with experience ranging from various study and Pre-FEED projects through the EPC phase

Role: Analyzing and summarizing engineering, construction, and operating requirements and impacts

Sub-Contractor

University of California, Irvine

- Advanced Power and Energy Program (APEP) addresses the development and deployment of efficient, environmentally sensitive, sustainable power generation and energy conversion
- Performed air quality and health impacts analysis for the CARB 2022 Scoping Plan update

Role: Evaluating emissions factors for this Analysis

Sub-Contractor

BW Research Partnership

- Deep expertise in evaluating jobs, workforce and economic development impacts of policies
- Experience evaluating labor, supply chain needs and the economic impacts of hydrogen production, storage and distribution

Role: Evaluating employment impacts for this Analysis

Sub-Contractor

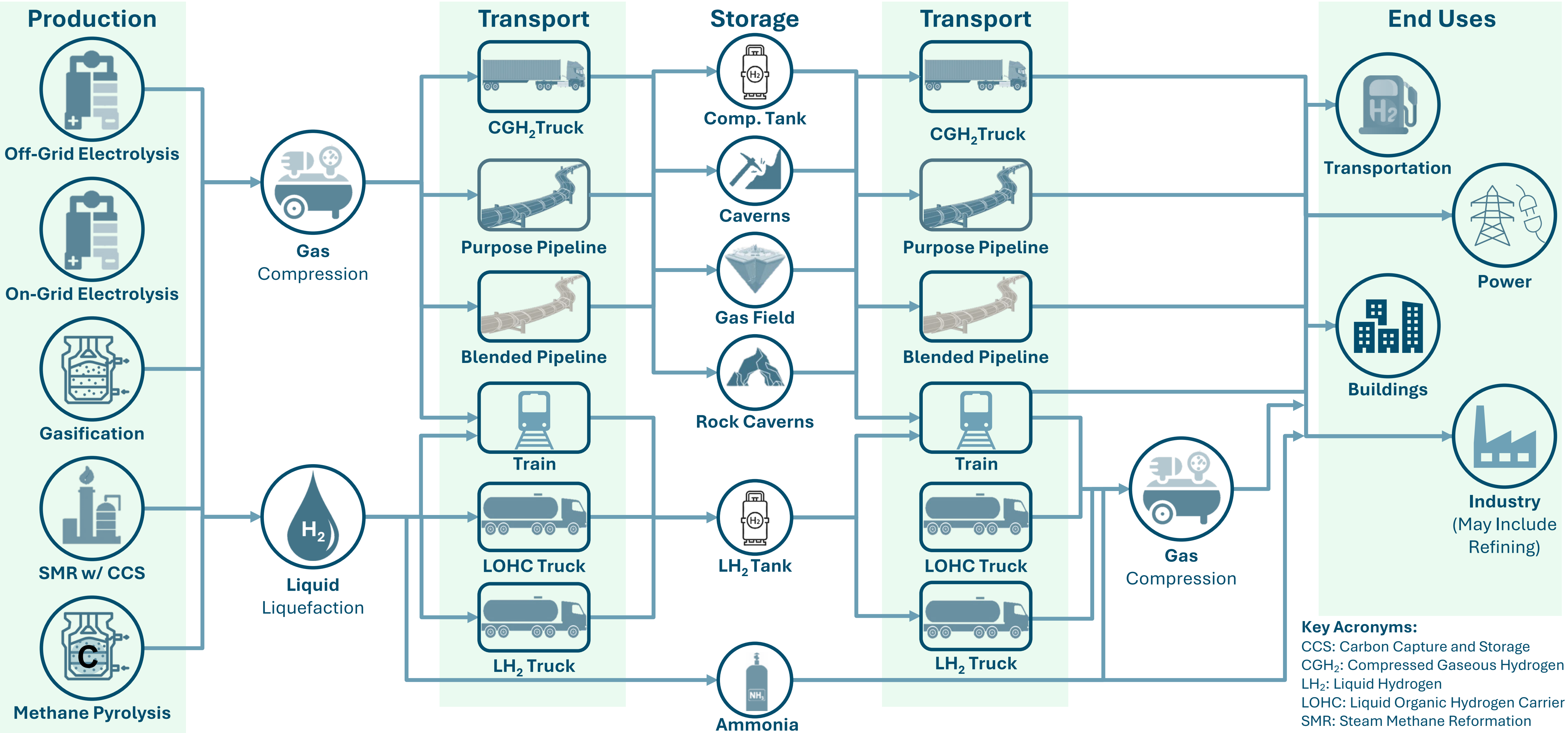
Summary of Scope of Work

The Project will cover a range of topics through comprehensive and cross-cutting analysis

Task	Description	Key Date(s)	
1	**Project Administration** • Stakeholder coordination • Public updates	• Public Workshop: February 2025 • CARB to Confirm Timing of Future Updates	
2	**Evaluation of Hydrogen Production Options, Needs, and Impacts** • Assessment of production costs, Technology Readiness Level, efficiencies, volumes, and permitting needs • Assessment of production impacts on emissions, natural resources and labor	• Analysis Conducted Q3-Q4 2024 • Findings To Be Incorporated in Final Analysis	*Addressed in today's Workshop*
3	**Hydrogen Transmission & Distribution Options, Needs, and Impacts** • Emissions, land use, and other impacts, including leakage assessment • Cost of transmission & distribution options		
4	**Hydrogen End-Use and Storage Options, Needs, and Impacts** • Quantitative assessment of hydrogen demand impacts by end-use • Assessment of hydrogen usage impacts		
5	**Impacts on Clean Air Objectives and Air Quality** • Synthesis of analysis from Tasks 2, 3, and 4 to isolate air quality data and conclusions • Qualitative and quantitative assessment of clean air objectives & air quality impacts	• Analysis Conducted Q4 2024 – Q2 2025 • Findings To Be Incorporated in Final Analysis	*Will be addressed in Final Analysis*
6	**Readiness/Barriers Analysis for Hydrogen Use and Scaling** • Assessment of labor and electric sector impacts of different hydrogen pathways • Assessment of transmission, distribution, and blending		
7	**Strategy and Policy Recommendations for Increased Hydrogen Production & Use** Recommendations for hydrogen strategy, policy, economy-wide usage, and regulatory processes		
8	**Final Analysis for Report** Progress Report → First Draft of Analysis → Draft of Analysis → Final Analysis	• Final Materials: Q3 2025 *Note: Final Analysis described here is distinct from CARB's Final SB 1075 Report*	

Given the breadth and depth of the Scope of Work, it is critical to balance analytical value with the time and effort necessary to conduct a given analysis

Hydrogen Pathways Considered in the Analysis



Key Acronyms:
CCS: Carbon Capture and Storage
CGH_2: Compressed Gaseous Hydrogen
LH_2: Liquid Hydrogen
LOHC: Liquid Organic Hydrogen Carrier
SMR: Steam Methane Reformation

E3 is seeking input from the Public on any key evidence and considerations the Team should incorporate into our coverage of specific pathways in the Analysis

Progress Update:
Methodologies and Initial Findings

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Hydrogen Production

Methodologies and Initial Findings

Hydrogen Production: Topics Covered

1) **Technology Readiness Levels of Hydrogen Production Options**
2) Infrastructure and **Resource Requirements for Hydrogen Production**
3) Permitting and Local Requirements for Hydrogen Production
4) Labor Requirements for Hydrogen Production
5) Emissions Factors Associated with Hydrogen Production
6) Impacts of Intermittent Versus Continuous Production of Hydrogen
7) **Life Cycle Assessment (LCA) of Hydrogen Production Pathways**
8) Fuel Conversion Efficiency Analysis of Hydrogen Production Options
9) **Hydrogen Production Cost Range**
10) **Scalability Assessment of Hydrogen Production Options**

These topics will be covered in the Analysis being prepared by the Team on Hydrogen Production; in this Workshop, we will focus on the bolded topics in this list, which represent the areas where more initial analysis has been completed and is not meant to convey priority of importance

Key Production Pathways

The choice of production pathways shapes key downstream analyses

This Analysis will focus on four production pathways:

Production Pathway	Technology / Feedstock Sub-Types	Feedstock Sources**
1 Electrolysis With Zero Carbon Power	• Alkaline • PEM • SOEC*	
2 SMR	• Fossil Gas • Biomethane • With CCS	Biomethane: • Landfill Gas • Livestock (Dairy) • Landfill Diverted Organic Waste • Wastewater Treatment
3 Methane Pyrolysis*	• Fossil Gas • Biomethane	(Biomethane sources above)
4 Gasification	• Biomass • With CCS	Biomass: • Forest Residue • Urban Wood Waste • Crop Residue

* Higher Development Uncertainty. Extent of inclusion of these pathways in full modeling analysis is subject to further research and findings.
** Feedstock sources shown here were identified in the state's 2022 Scoping Plan.

Key Acronyms:
PEM: Proton Electron Membrane
SOEC: Solid Oxide Electrolyzer Cell
SMR: Steam Methane Reformation
CCS: Carbon Capture and Storage

This covers a broad range of pathways; while additional pathways exist, lower Technology Readiness Levels, potential feedstock scarcity, relative commercial competitiveness, and emissions impacts are some of the reasons they will not be evaluated in this analysis.

Technology Readiness Levels of Hydrogen Production Options

The level of uncertainty associated with being able to deploy different production pathways at scale will differ by technology type

- **Literature review was conducted with key findings presented on the right**
- **Reformation is a mature and widely deployed technology however addition of CCS introduces uncertainty and risk**
  - Novel types of reformation such as autothermal and partial oxidation from gas are not as widely deployed as conventional SMR
- **Alkaline and PEM electrolyzers, while not widely deployed, especially in the US, have high TRLs**
- **SOEC electrolysis, gasification and pyrolysis are all promising but have lower TRLs today and thus carry higher uncertainty and risk**

Production Technology	Current TRL	Global and Domestic Production Capability
Alkaline Electrolysis	9	Domestic: <1 GW/year i.e., < 0.1 MMT/year[1] Global: 40.9 GW/year
PEM Electrolysis	9	Domestic: <1 GW/year Global: 12.1 GW/year
Solid Oxide (SOEC) Electrolysis	8	Domestic: <1 GW/year Global: 1.2 GW/year
Reformation	9	Domestic: ~10 MMT/yr Global: ~53.2 MMT/yr[1]
Reformation + CCS	6-9	Domestic: Limited operational capacity Global: ~.00424 MMT/yr
Biomass Gasification	7-8	Limited global operational capacity
Biomass Gasification + CCS	6-8	No global operational capacity
Pyrolysis	8	Domestic: ~0.0051 MMT/yr Global: ~0.0052 MMT/yr

1) Assuming 75% capacity factor and 52kWh/kg electricity needed, the hydrogen produced from 1, 12, and 40 GW electrolyzers will be about 0.1, 1.5 and 5 MMT/yr.

Conventional SMR is the only technology that is both widely deployed and has a high TRL, while alkaline and PEM electrolysis have high TRLs and relatively high global deployment but limited domestic experience; remaining pathways have relatively lower TRL and deployment levels today

Resource Requirements for Hydrogen Production

California-specific considerations of input needs and impacts will be essential to scaling the hydrogen industry

- **The Project Team conducted a literature review to estimate land, water, feedstock and/or electricity requirement for different pathways**
  - Estimates for alkaline electrolysis are presented as an example
- **These requirements were then scaled up to the total hydrogen demand in 2045**
- **This will help policymakers develop intuition for the scale of total natural resource needs for the hydrogen economy and evaluate tradeoffs between different pathways**
- **The final analysis will also discuss operational infrastructure including water and wastewater treatment, road and rail transportation for biomass, natural gas or carbon dioxide pipelines, etc.**

Water Requirement to Meet 2045 Hydrogen Demand for Selected Pathway

Pathway	Liters of water/kg of H2	Total Hydrogen Demand in 2045 (MMT)	Total Water Requirement (Billions of Liters)
Alkaline Electrolysis with Solar	44	1.6	72

Land Requirement to Meet 2045 Hydrogen Demand for Selected Pathway

Pathway	Land Requirement Solar (km^2)	Land Requirement Electrolyzer (km^2)	Total Electricity Demand for Hydrogen (TWH by 2045)	Total Land Impact for Hydrogen (km^2 by 2045)
Alkaline Electrolysis	809	3.4	85	812

Electricity Requirement to Meet 2045 Hydrogen Demand for Selected Pathway

Pathway	Metric (kwh/kg of H2)	Total Demand by 2045 (MMT)	Total Impact (TWH)
Alkaline Electrolysis	52	1.6	85

Note: *the Team has reviewed input requirements for other pathways not shown here. The values shown here are intended to demonstrate the extent of the Team's review for a given pathway.*

Electrolysis may require high levels of electricity, land, and water consumption, but these requirements may still be lower than certain fossil fuel pathways; it will be important to study and consider low-emissions non-electrolytic pathways as part of the state's overall production potential

Life Cycle Assessment (LCA) of Hydrogen Production Pathways

LCA helps understand GHG-intensity of hydrogen produced and determine 45V PTC eligibility

- **Well-to-gate GHG intensity of hydrogen produced via different pathways were estimated using GREET R&D 2023rev1**
- **Preliminary findings:**
  - Hydrogen produced via electrolysis with the average grid electricity is currently very carbon intensive. Intensity reduces over time as renewables are deployed
  - Addition of CCS helps reduce the intensity of hydrogen produced via SMR significantly – both using natural gas and biomethane; however natural gas remains carbon-positive due to methane leakage upstream and a 96% CO2 capture rate post reformation.
  - Biomass gasification has a low carbon intensity because CO2 released is then absorbed by plants which are then gasified, leading to a net-neutral cycle. Adding CCS can make it carbon-negative
  - Pyrolysis has a low carbon intensity given the reaction product is solid carbon that can be easily captured
  - Pathways using biomethane can be carbon-negative when compared to the counterfactual where the methane from the degrading waste escapes into the atmosphere contributing to global warming

Production Pathway	Sub-Type	Well-to-Gate kg CO_2e/kg H_2
Electrolysis	PEM CA Grid Mix 2025	9.2
	PEM CA Grid Mix 2045	3.3
	PEM - Solar	0
SMR	Natural Gas	11.5
	Municipal Solid Waste Gas	6.9
	Waster Water Treatment Gas	5.6
	Landfill Gas	2.9
	Livestock/Dairy Gas	-42.1
SMR with CCS	Natural Gas	2.9
	Municipal Solid Waste Gas	-2.0
	Waster Water Treatment Gas	-3.3
	Landfill Gas	-6.3
	Livestock/Dairy Gas	-54.1
Biomass Gasification	Ag. Residue	1.0
	Forest Residue	1.0
Biomass Gasification with CCS	Ag. Residue	-20.7
	Forest Residue	-22.6
Pyrolysis	Natural Gas	1.8
	Municipal Solid Waste Gas	0.9
	Waster Water Treatment Gas	0.2
	Landfill Gas	-0.6
	Livestock/Dairy Gas	-12.8

All major pathways evaluated here may produce low-carbon H2, but effective CCS and low upstream methane leakage are crucial for SMR with fossil gas and certain types of biomethane, while certain carbon-negative pathways can be used to produce H2 and offset emissions from hard-to-decarbonize end-uses

Hydrogen Production Cost Range

Critical to understanding the potential for scaling hydrogen production to meet demand forecasted in the Scoping Plan and the economic impact on end-users

Level of Impact of Various Factors on Production Cost

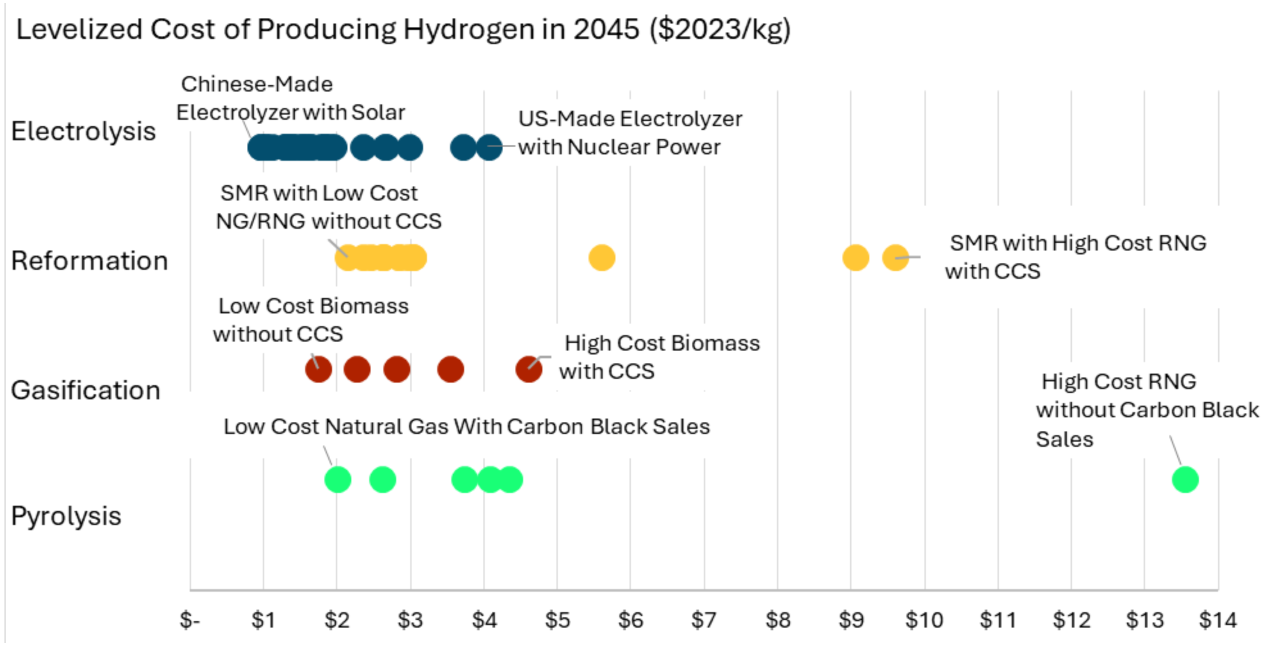
Production Pathway	Feedstock Cost	Electricity Cost	Capital Cost	Lifetime Improvements	Load Factor	Efficiency	Carbon Management Cost	By-Product Sales
Alkaline Electrolysis	Low	Mid-High	High	Mid	High	Mid	NA	NA
PEM Electrolysis	Low	Mid-High	High	Mid	High	Mid	NA	NA
Solid Oxide Electrolysis	Mid	Mid-High	High	High	High	Mid	NA	NA
Steam Methane Reformation (SMR)	High	Low	Mid	Low	Low	Low	NA	NA
SMR + CCS	High	Low	Mid	Low	Mid	Mid	Mid	NA
Biomass Gasification	High	Low	Mid	Low	Low	Low	NA	Mid
Biomass Gasification + CCS	High	Low	Mid	Low	Mid	Mid	Mid	Mid
Methane Pyrolysis	High	Mid	Low	High	Mid	Mid	Low	High

- **Hydrogen production costs are highly uncertain, but knowing which factors have the most impact has helped quantify the uncertainty**
- **The matrix above was developed based on research and preliminary cost calculations**
- **Using this matrix, several scenarios were developed to estimate production costs reported on the next slide**

Hydrogen Production Cost Range

Critical to understanding the potential for scaling hydrogen production to meet demand forecasted in the Scoping Plan and the economic impact on end-users

- **Production cost forecasts were calculated from 2025-2045 across different pathways and scenarios, varying the high impact factors and some mid impact factors presented on the previous slide**
- **Cost forecasts from 2045 suggest that:**
  - There is a wide range of costs with each pathway, highlighting the uncertainty. There is meaningful overlap between pathways indicating we cannot pick a single winner based on cost
  - Electrolyzers made in China cost less than those manufactured in the U.S. today. Further cost declines and pairing with good quality in-state solar may yield close to $1/kg H2
    - If U.S.-made electrolyzers do not come down the cost curve and are paired with expensive power sources, production may cost as much as $4/kg
  - The cost from Reformation and Gasification is heavily influenced by the fuel price (that can vary by source) and the cost of CCS
  - In addition to fuel price, the (net) cost of pyrolysis is also heavily influenced by revenue from carbon black sales



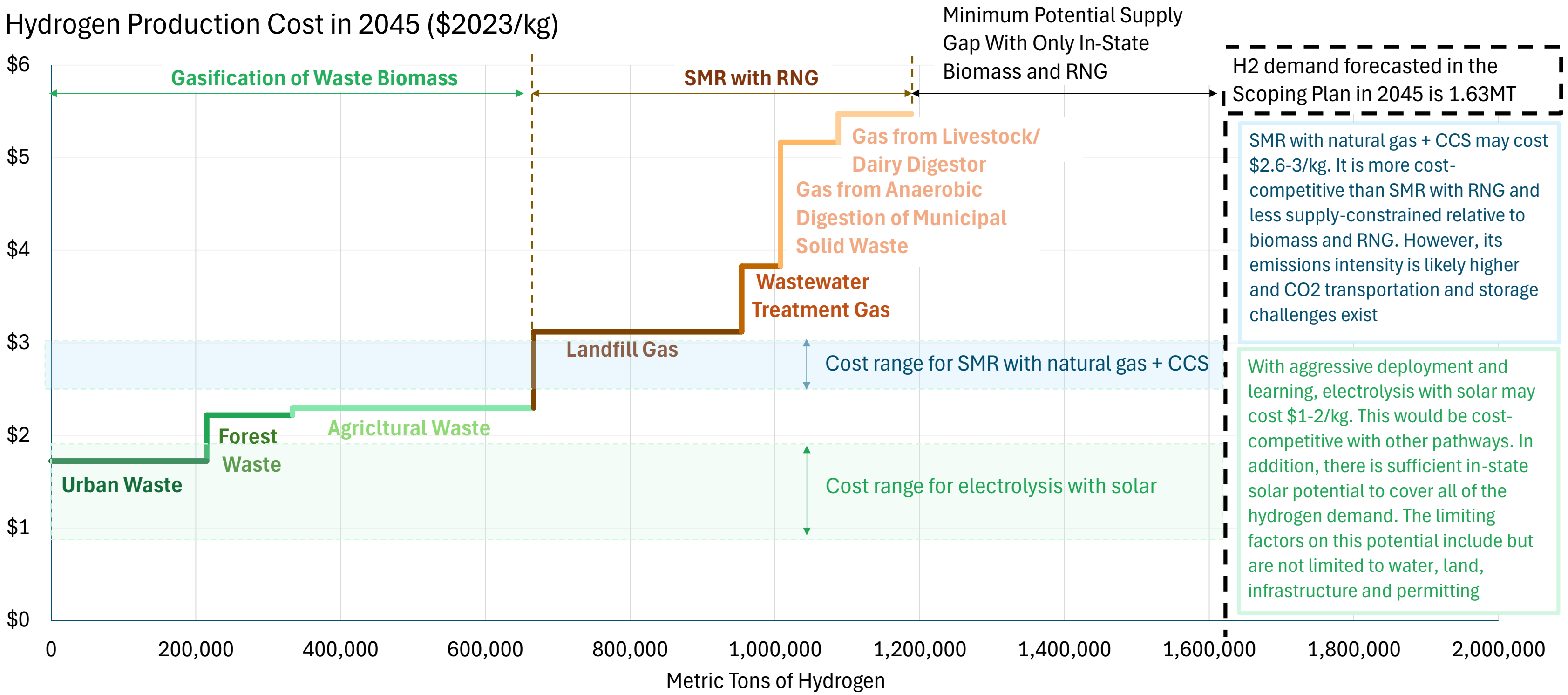
Note: Each circle represents a distinct scenario.

Producing H2 at $1/kg by 2045 is achievable with electrolysis under optimistic assumptions, but a wide uncertainty band exists for each pathway and there is meaningful cost overlap across pathways

Scalability Assessment of Hydrogen Production Options

Assessing California's ability to scale up its hydrogen production to meet 2045 demand in Scoping Plan

Hydrogen Supply Curve from In-State Biomass and RNG Compared to the Cost of SMR with Natural Gas + CCS and Electrolysis with Solar



SMR was assumed as the pathway for gas for illustration, given its higher maturity. Pyrolysis may also play a role, but the total amount of hydrogen that can be produced would be in the same order of magnitude with some adjustments needed for conversion efficiencies.

- **From a fuel/feedstock availability standpoint, it is found that even if all the biomass and biomethane available for new energy applications is dedicated to hydrogen production, it will not be sufficient; in practice, availability may be lower due to competing uses for these fuels**
- **This implies electrolysis most likely has a role to play; natural gas may also play a role if methane leakage and CO2 emissions are both minimized**
  - There is more than enough solar potential in the state to power the electrolysis; however, land use, water impacts, and potential local opposition may impact total available potential
- **The final analysis will include discussion on other aspects of hydrogen scalability such as siting, permitting and labor force requirements**

Meeting hydrogen demand in 2045 is possible, especially if a mix of different pathways are used; while there theoretically is enough solar to meet all demand with electrolysis, land use impacts and other factors warrant consideration of other pathways

Hydrogen Transmission & Distribution

Methodologies and Initial Findings

Hydrogen Transmission & Distribution: Topics Covered

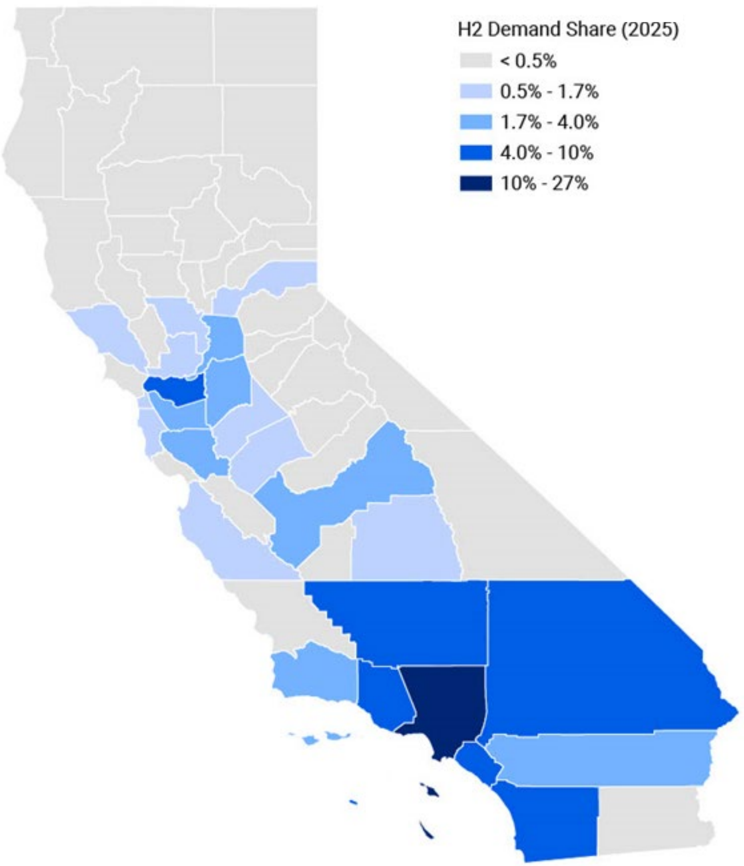
1) **Evaluation of Transmission & Distribution Options**
2) Transmission & Distribution Leakage Analysis
3) **Transmission & Distribution Cost Analysis**
4) Transmission & Distribution Emissions Impacts

These topics will be covered in the Analysis being prepared by the Team on Hydrogen Transmission & Distribution; in this Workshop, we will focus on the bolded topics in this list, which represent the areas where more initial analysis has been completed and is not meant to convey priority of importance

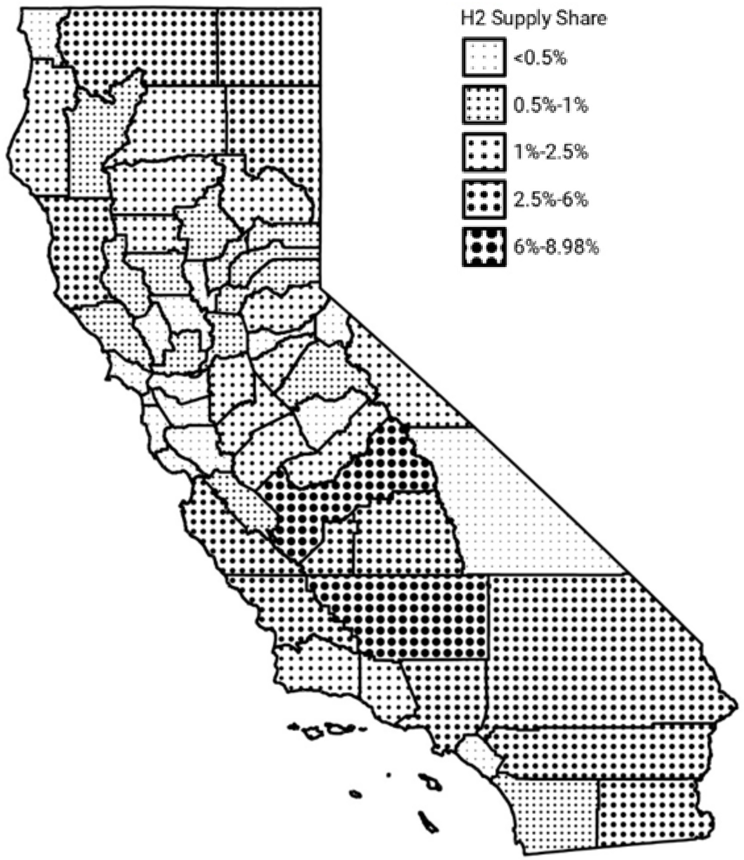
Evaluation of Transmission & Distribution Options

The distance between hydrogen demand and supply hubs will influence T&D choices

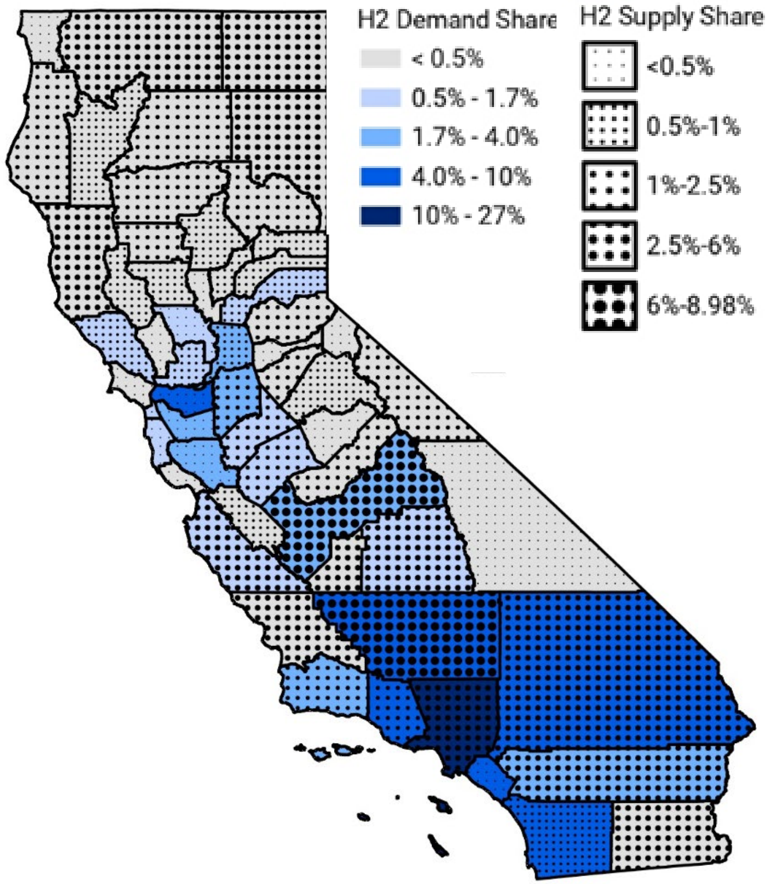
Hydrogen Demand for New Energy Applications by County (% of Statewide Demand in 2045)



Hydrogen Supply Potential Based on Solar, Wind and Biomass Potential (% of Statewide Potential)



Hydrogen Demand for New Energy Applications and Supply Potential by County



+ **Hydrogen demand is expected to be concentrated in and near the Bay Area and LA given commercial and industrial activities**
+ **Solar and biomass availability and thus hydrogen supply potential is dispersed**
  - Kern and Fresno County have the highest potential due to relative abundance of both solar and biomass

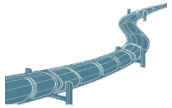
Most of the high-demand and high-supply counties do NOT overlap. Thus, while some opportunities for co-located production and use of hydrogen may exist, medium to long-range hydrogen transportation will be required

Evaluation of Transmission & Distribution Options

Linking supply with demand can take various paths, each with a potential role in the industry

- **In general, three categories of hydrogen T&D options exist:**
  1) **Co-location of production and potential, with pipelines** (note: distribution within hub may occur via smaller pipes or trucks)
  2) **Co-location of production and potential, with trucking** to end-use location
  3) **Co-location of production and demand**, assuming most of the electricity and feedstock to produce hydrogen is sourced locally with transport of remaining electricity and feedstock to demand center via power lines, trucks, pipes (in case of RNG), or trains
- **In addition to distance, the relative attractiveness of T&D options depends on the scale of the application, i.e., hydrogen throughput required**
- **Each T&D option has its pros and cons as it relates to upfront capital expenditures, levelized cost of transporting hydrogen over the lifetime of the asset, leakage, land use impacts, etc. that will be explored in more detail in the final analysis**

Feasible Hydrogen Distribution Options for Demand, for Selected End-Use Categories

End-Use Category	Distribution Method (Options)
On-Road Vehicles Aviation Oil & Gas Extraction	
Ocean-Going Vessels	
Rail	
Industry (Including Petroleum Refining) Residential & Commercial Buildings Transportation, Communication, and Utilities (TCU)	

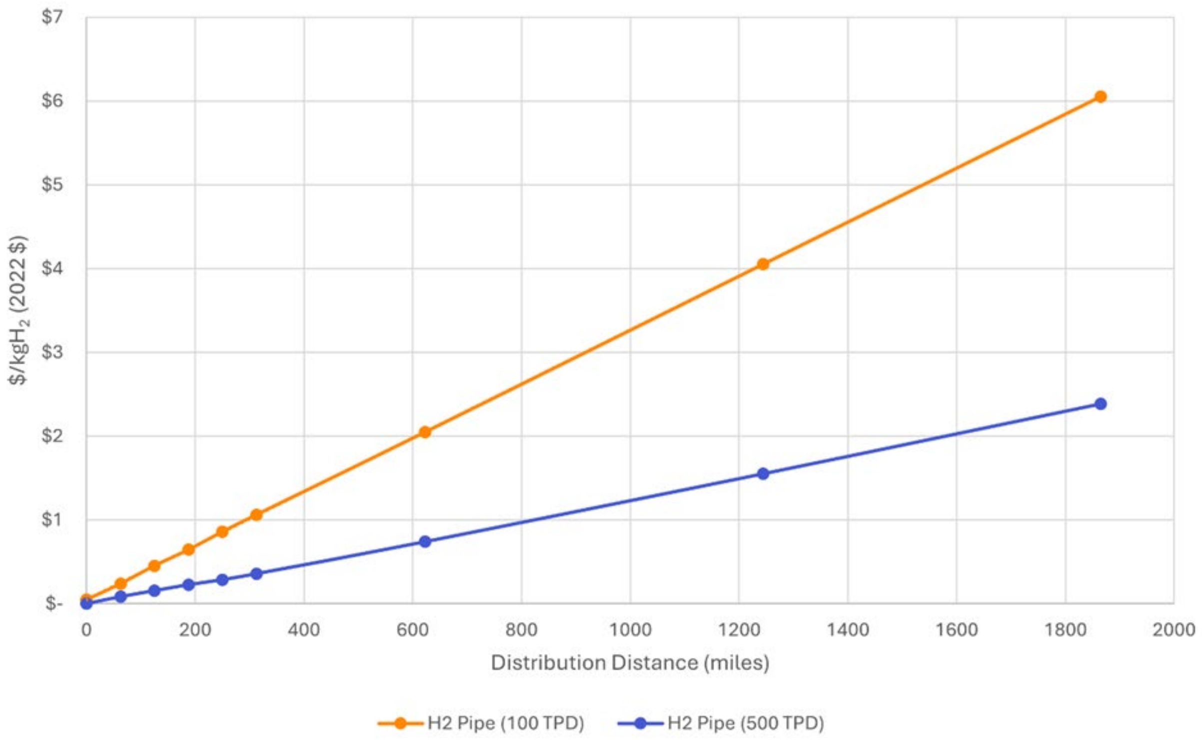
No single T&D option is likely to be optimal for all hydrogen users across the state. Pipelines, trucks and other mediums may all play a role based on distance from hydrogen supplier, throughput required and other factors

Transmission & Distribution Cost Analysis

The cost of T&D will be driven by method chosen, distance between supply and demand locations, and total amount transported

- **Hydrogen's low energy density on a volumetric basis means that transporting it over long distance presents a unique challenge from a cost perspective**
- **Costs are being evaluated for pipeline, trucking, shipping, and alternative hydrogen carrier options (e.g., ammonia, liquid organic hydrogen, and methanol)**
- **In addition, the Team is also studying the Angeles Link project as a case study of transmission and distribution options and potential impacts**
- **Preliminary research for pipeline-based transportation shows a cost of $0.4-1/kg H2 over 300 miles, the approx. distance between Kern County and the Bay Area**

Hydrogen Transportation Cost via Pipelines as a Function of Distance Transported ($/kg H2, $2022)



Transmission and distribution cost will always increase with distance and could be a non-trivial contributor to the delivered cost of hydrogen; minimizing distances between supply and demand therefore becomes an industry development catalyst, unless T&D costs can be reduced below expectations

10 Minute Break

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Hydrogen End-Use

Methodologies and Initial Findings

Hydrogen End-Uses: Topics Covered

1) Safety Considerations for Hydrogen End-Uses
2) **Potential Hydrogen Demand by End-Use**
3) GHG Emissions Impacts of Hydrogen End-Uses
4) Criteria Emissions, Toxic Pollutant Emissions, and Air Quality Impacts of Hydrogen End-Uses
5) **Hydrogen End-Use Cost Analysis**
6) **Evaluation of Hydrogen Relative to Other Clean Alternatives by End-Use**
7) **Environmental Justice Impacts of Hydrogen End-Uses**
8) **Blending Impacts on Hydrogen End-Uses**
9) Catalytic Impacts Assessment

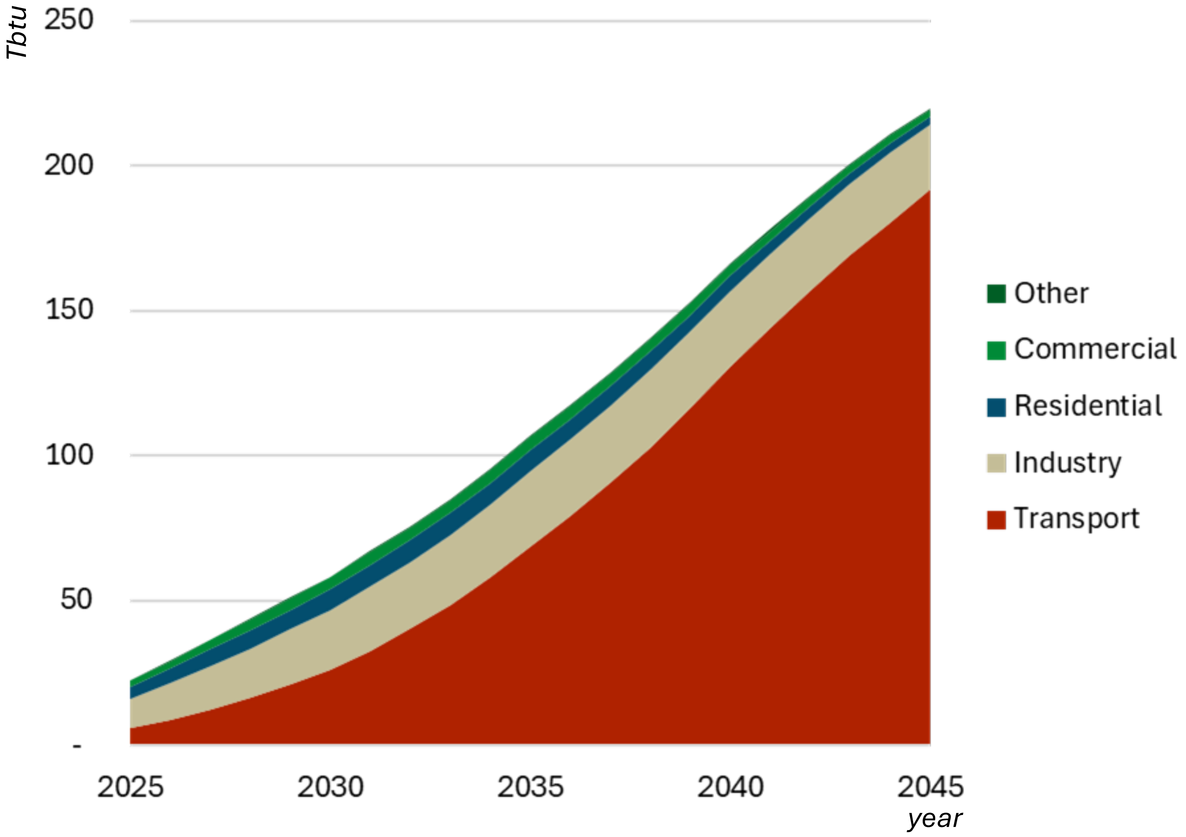
These topics will be covered in the Analysis being prepared by the Team on Hydrogen End-Uses; in this Workshop, we will focus on the bolded topics in this list, which represent the areas where more initial analysis has been completed and is not meant to convey priority of importance

Potential Hydrogen Demand by End-Use

Total costs, natural resource requirements, air quality and health benefits will be quantified for this demand

- **Hydrogen demand for new energy applications was sourced from the state's 2022 Scoping Plan**
- **Heavy duty transportation and high-temperature industrial heating will account for most energy demand from hydrogen**
- **Hydrogen use in residential and commercial buildings will be limited; electrification plays a bigger role**
- **Hydrogen is assumed to be blended up to a 7% energy limit into the gas distribution system**
- **Hydrogen may also help maintain electric reliability as a seasonal storage medium, which will be studied in more detail on this project**
- **The hydrogen landscape is constantly evolving**
  - Additional use cases for hydrogen may materialize; the final materials will acknowledge but not quantify these additional use cases
  - The objective of this project is to assess the state's readiness to meet this level of demand and understand its implications, which will provide a starting point for the conversation on whether lower or higher levels of hydrogen demand can be met

Final Energy Demand From Hydrogen, Non-Electric End-Uses



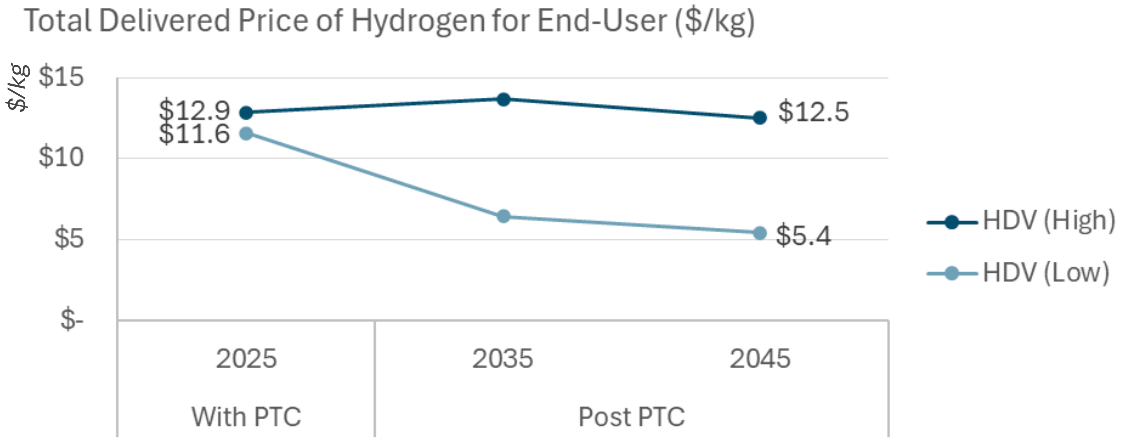
Other includes some Transportation, Communication and Utilities (TCU) related end-uses not captured in other categories.

Hydrogen can be used to decarbonize hard-to-electrify end-uses such as heavy-duty transportation and high-temperature industrial processes

Hydrogen End-Use Cost Analysis

Cost of using hydrogen relative to several fossil incumbent uses illustrates impact on end-users

+ **Delivered price of hydrogen includes the cost of electrolysis with solar, transportation, storage and fuel dispensing**
  - The 45V Production Tax Credit (PTC) through 2035 is also incorporated
+ **A cost premium of $0.1-0.6M/truck is estimated for a hydrogen truck owner in the long-term relative to the cost of owning a diesel truck**
+ **No other incentives for hydrogen, nor penalties on fossil are assumed to illustrate the cost difference in the absence of these measures**
+ **Preliminary analysis of other transportation and industrial heating applications also suggest a green premium**
  - These will be presented in the final analysis



Total truck capital expenditures and lifetime fuel and maintenance costs with diesel and green hydrogen ($M/truck)

2025			2035			2045		
Diesel	Green H2	Cost Δ	Diesel	Green H2	Cost Δ	Diesel	Green H2	Cost Δ
0.5	1.0-1.3	**0.5-0.8**	0.5	0.7-1.1	**0.2-0.6**	0.5	0.6-1.1	**0.1-0.6**

Note: *the Team is estimating costs requirements for other end-uses not shown here. Values shown here are intended to demonstrate the extent of the Team's review for a given use.*

Without incentives, even in an optimistic scenario, delivered price of hydrogen for trucking may reach $5.4/kg by 2045 in $2024. This would be equivalent to $6/gal of diesel on an energy basis. CA-average diesel price today is $4.7/gal

Evaluation of Hydrogen Relative to Other Clean Alternatives by End-Use

The competitiveness of hydrogen relative to alternatives will vary by end-use

- **Hydrogen is one of several decarbonization measures that exist for each end-use**
- **The analysis will identify the best clean alternative to hydrogen for key end-uses**
- **Advantages and disadvantages of hydrogen relative to the alternative will be presented**
- **The analysis will include a qualitative discussion on scenarios in which hydrogen may become the key decarbonization measure for a given end-use, instead of a potential alternative**

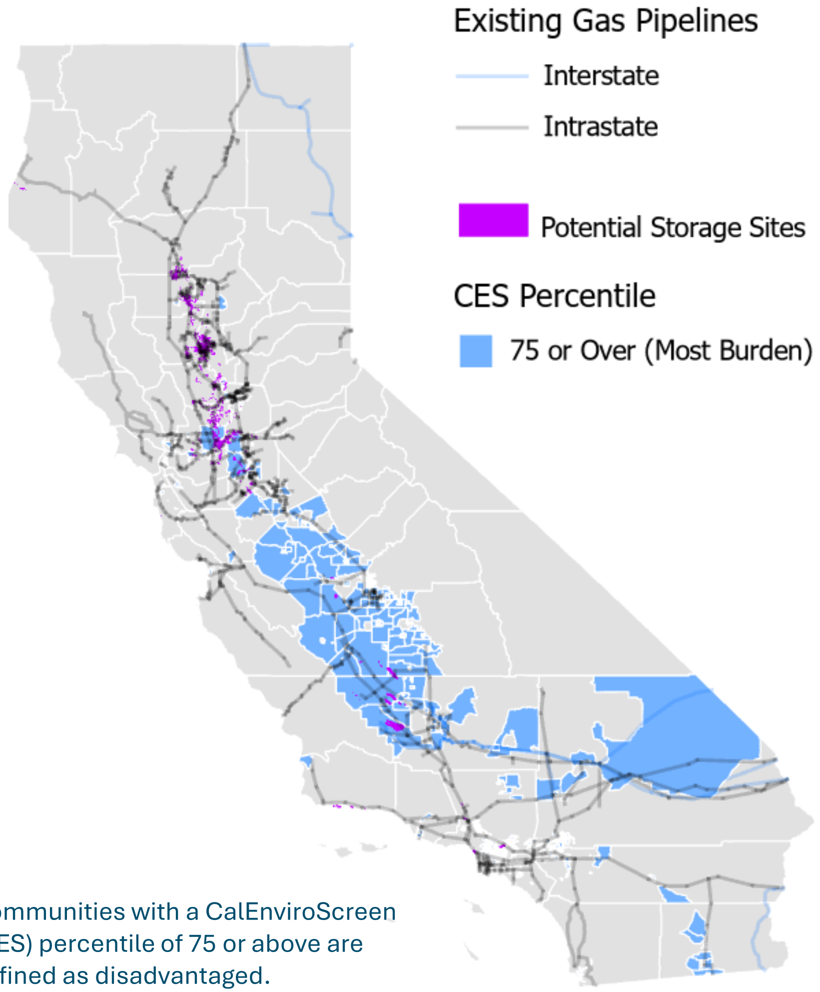
Sector	End-Use	Clean Alternative to Hydrogen
Transportation	LDV	Electrification
	MDV	Electrification
	Short-Haul HDV	Electrification
	Long-Haul HDV	Electrification
	Off-road vehicles and equipment	Biofuels
	Aviation	Biofuels
	Ocean-Going vessels	Biofuels
	Port Operations	Electrification
	Rail	Electrification
Buildings	Existing natural gas (e.g., heating, drying, cooking, etc.)	Electrification
Industry	Low-temperature industrial heat	Electrification
	High-temperature industrial heat	Biofuels
	Petroleum refining, ammonia manufacturing	None as a reagent. See above for heat
	Drinking water treatment	Renewable electricity
Electric Reliability	Peaking applications with long duration energy storage (LDES)	Multiple emerging technology alternatives

Hydrogen may compete against biofuels and other emerging technologies for hard to electrify end-uses but uncertainty exists

Environmental Justice Impacts

Hydrogen infrastructure development should consider and reflect potential impacts on local communities

Locations of Existing Gas Pipelines, Potential Hydrogen Storage Sites and Disadvantaged Communities[1]



(1) Communities with a CalEnviroScreen (CES) percentile of 75 or above are defined as disadvantaged.

Infrastructure	Basis	% Overlap with Disadvantaged Communities
Solar Area	Suitable Land Area	23%
Wind Area	Suitable Land Area	16%
Natural Gas Pipeline	Miles of Existing Pipeline	13%
Major Highway Miles	Miles of Roadway	17%
Underground Storage Sites	Reservoir Area	46%
Existing Gas-Powered Electricity Generators	Nameplate Capacity	28%

- **Hydrogen demand is expected to be concentrated in and near the Bay Area and LA given commercial and industrial activities**
- **Disadvantaged communities are concentrated in the Central Valley and San Bernardino county where both demand for hydrogen may exist as well as key infrastructure to produce, store and transport the hydrogen needed in these demand centers may need to be sited**
- **Preliminary analysis suggests that in some cases, as with underground storage, the overlap is meaningful and potentially unavoidable**
- **Existing gas infrastructure locations were studied as a subset of these may be re-purposed or replaced with hydrogen-ready infrastructure**

Hydrogen infrastructure may need to be sited in the Bay Area and Los Angeles, and transportation and/or storage between these demand hubs may overlap with historically disadvantaged communities; potential risks should be managed and mitigated to ensure communities benefit from jobs and improved air quality

Blending Impacts on Hydrogen End-Uses

Blending hydrogen with natural gas can help reduce GHG emissions but may be challenging for different applications or pathways

+ **Hydrogen blending has multiple potential end-uses or applications worth considering:**
  - Hydrogen may be blended with natural gas for power generation
  - Residential or commercial users may rely on blended pipeline gas for boilers, furnaces, or other appliances
+ **Both general and end-use specific considerations for potential hydrogen blending are being analyzed in this Project, including blending for power generation with natural gas:**
  - Blending hydrogen with natural gas for power generation requires modifying turbines to account for hydrogen's unique combustion characteristics (e.g., hydrogen has a higher flame speed than natural gas, so new turbines are being designed to accommodate higher fluid velocities while maintaining efficient and complete combustion)
  - Combusting hydrogen can produce more NOx than gas due to the higher temperature, but OEMs are working on new designs to minimize NOx production
  - The fuel gas system also needs to be analyzed and retrofit at appropriate blend limits; Where retrofits are needed will be very specific to vendor, technology and asset vintage
  - Since hydrogen contains less energy per unit volume than natural gas, the blended fuel will need to be delivered at a higher volumetric flow rate to achieve the same heat input as natural gas, assuming no increase in pressure
  - Mechanical fittings and joints, which are produced in a wide variety of materials and designs, should be evaluated on a case-by-case basis to ensure compatibility

High levels of hydrogen blending will require retrofits given hydrogen's unique chemical and physical properties; the blend-level at which retrofits are needed will vary based on vendor, asset material, asset vintage, and other factors

Summary of Key Questions for Public Comment

Energy+Environmental Economics

Previous Feedback Provided to CARB

- **The Team acknowledges and appreciates the feedback provided in September 2023 in response to CARB's "Hydrogen Deployment, Development, and Use Kickoff Workshop"**
- **In response to the feedback provided in September 2023, E3 would like to note the following:**
  - This Analysis will build on the Scoping Plan, and is not intended to replace it
  - This Analysis is designed to be technology-agnostic and will include an assessment of both electrolytic *and* non-electrolytic production pathways
  - The carbon intensity of each modeled production pathway is being evaluated to the extent possible
  - Infrastructure and permitting needs are being holistically studied
  - *Opportunities* for hydrogen in hard-to-electrify sectors and to maintain electric reliability are being studied in conjunction with the *risks* and potential negative impacts of hydrogen to produce a thorough, balanced perspective

For More Detail: https://ww2.arb.ca.gov/public-comments/sb-1075-report-hydrogen-deployment-development-and-use-kickoff-workshop

Summary of Key Questions for Public Comment

Public stakeholder input on this Analysis is requested to inform the final product

The Team invites the Public to provide input on the following questions to support the development of this Analysis and, separately, CARB's SB 1075 Report:

Question	Relevant Slide(s), by Slide Title
1) If you are currently planning or developing a hydrogen project, can you please share specific cost sources that can be considered in the analysis?	• Scalability Assessment of Hydrogen Production Options • Hydrogen Production Cost Range • Transmission & Distribution Cost Analysis
2) Are there examples of improvements in input efficiencies of the hydrogen production pathways discussed in this Workshop that should be reflected in the analysis of options for scaling production?	• Resource Requirements for Hydrogen Production
3) Are there additional infrastructure needs or impacts that should be considered in the Analysis? If so, please describe.	• Summary of Scope of Work • Hydrogen Production: Topics Covered • Hydrogen Transmission & Distribution: Topics Covered • Hydrogen End-Uses: Topics Covered
4) Is there any additional evidence or <u>recent</u> analysis that you would recommend for consideration in preparing this Analysis (e.g., recent white papers, public reports, data sources, policy recommendations developed for a different region, etc.)?	General request for input.

As a public analysis and product, Public input will be critical to ensuring the final product is meaningful and constructive

Appendix

Energy+Environmental Economics

Permitting and Local Requirements for Hydrogen Production

Permitting requirements will vary across pathways and specific sites

In general, it is likely that hydrogen production projects under all pathways would be subject to review under the California Environmental Quality Act (CEQA); beyond CEQA, the following permitting and local requirements are relevant to hydrogen:

Air Permits

+ **APCDs / AQMDs:** Each of California's 35 Air Pollution Control Districts (APCDs) or Air Quality Management Districts (AQMDs) are responsible for implementing federal and state air pollution regulations and issuing air permits specific to their air quality issues and rules
+ **NSR:** The construction permit application process entails New Source Review (NSR) under the California Clean Air Act and federal Clean Air Act
+ **Operating Permits:** Pre-construction permits (NSR permits) typically only authorize construction and initial start-up commissioning of new or modified air emissions sources; authorization of long-term operation of a hydrogen production project will require an operating permit
+ **Air Permitting for Nonattainment Counties:** Given most counties in California are listed as being in nonattainment (i.e., failing to meet EPA or CA air quality standards) for at least one air pollutant, air permitting will have an important role in the permitting process for hydrogen projects

Water Permits

+ **Water Source Permits:** Likely to be necessary but will vary considerably based on location (e.g., municipal permitting is different than surface water and groundwater permitting) and production pathway water requirements vary significantly
+ **Wastewater Discharge Permits:** Also required to discharge wastewater from a hydrogen production facility, with requirements depending upon where the water is discharged to, the pollutant levels in the discharge water, and the type of water that is discharged
+ **Clean Water Act Discharge Permit:** Under the Clean Water Act, discharges of stormwater that may contain contaminants is prohibited unless in compliance with a federal permit
+ **Other Water Permits:** Disturbances to water bodies and wetlands may require permits at the federal and state level

Environmental Permits / Processes

+ **NEPA:** Any hydrogen production projects with a federal nexus, including being located on federal land, receiving federal funding, or requiring federal approval will be subject to National Environmental Policy Act (NEPA) review
+ **CEQA:** Not a permit, but a process that requires public agencies and local governments in California to consider environmental consequences before approving plans and committing to a course of action

Other Permits

+ **Chemical Storage and Handling:** Chemical storage and use at hydrogen facilities would be subject to chemical reporting and handling requirements under various federal, state, and local programs
+ **ITP:** Threatened and endangered species concerns vary from project to project but may require an Incidental Take Permit (ITP), which requires NEPA review

Federal, state, and local policy and regulations play a role in increasing or reducing the attractiveness of different production pathways and may increase or decrease the relative attractiveness of different potential project development sites

Transmission & Distribution Leakage Analysis

Leakage may occur for a variety of reasons, and best practices exist to minimize leakage

+ **Leak sources can include joints (e.g., flanges, welds), components (e.g., valves), seals, and pipe / tubing, similar in nature to leak sources in natural gas systems**
+ **Best practices to minimize leakage include:**
  1) **Planning and design**: the selection of materials, testing of components, verification of leak tightness, and minimization of the number of joints can reduce leakage potential before construction and operation
  2) **Installation, commissioning, and operation**: inspection during construction, testing of components during commissioning, and implementation of leak detection and repair programs can all minimize the potential for and damages from leakage during construction and operations
+ **The Team's investigation of hydrogen leakage in transmission and distribution focuses on low volume, external releases of hydrogen from these systems**
  - While significant hydrogen leaks may be associated with accidents or failures, which are unlikely to occur, low volume leakage associated with normal operation is challenging to quantify

While existing literature on hydrogen leakage is limited, lessons from natural gas and best practices from chemical sciences and engineering can be applied to mitigate risk and potential damages from hydrogen leakage as the industry grows

Safety Considerations for Hydrogen End-Uses

- **Given its low volumetric energy density, hydrogen will likely be transported and stored as a high-pressure gas or in a liquefied state under cryogenic temperatures**
  - Safety considerations exist with these high-pressure/low-temperature operating conditions for people in the vicinity of the hydrogen infrastructure
- **If hydrogen leaks, ignition and asphyxiation risks may exist based on the nature and location of the leakage**
- **While hydrogen's physical and chemical properties are unique, these risks are not: similar risks also exist with widely used fossil fuels and chemicals**
  - Hydrogen has also been used for decades in applications such as ammonia and methanol manufacturing and petrochemical refining worldwide
- **Safety measures exist and are implemented in these applications**
  - However, as hydrogen use expands into new energy applications, it is important to continue studying known and new safety risks and ensure appropriate safety measures are adopted
- **The final analysis will contain more details on this topic**

Thank You

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