Energy+Environmental Economics

Hydrogen Opportunities in a Low-Carbon Future

An assessment of long-term market potential for hydrogen in the Western United States

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Executive Summary

Study for ACES, a joint development project between Mitsubishi Hitachi Power Systems Americas, Inc. and Magnum Development, LLC

IAEE 2021 Online Conference

Executive Summary Outline

+ Project Overview
+ Hydrogen Production Costs and Levelized Cost of Energy
+ Hydrogen Outlook in the Power Sector
+ Hydrogen Outlook in Buildings, Transportation and Industry
+ Supply Chain Overview

Full report available at www.ethree.com

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This report has been prepared by E3 for ACES, a joint development project between Mitsubishi Hitachi Power Systems Americas, Inc. and Magnum Development, LLC. This report is separate from and unrelated to any work E3 is doing for the California Public Utilities Commission. While E3 provided technical support to Mitsubishi Hitachi Power Systems Americas, Inc. and Magnum Development in preparation of this report, E3 does not endorse any specific policy or regulatory measures as a result of this analysis. The California Public Utilities Commission did not participate in this project and does not endorse the conclusions presented in this report.

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Project Overview

Context, Approach and Key Findings

Study Objectives

+ **The ACES joint development project between Mitsubishi Hitachi Power Systems Americas, Inc. (MHPS) and Magnum Development, LLC (Magnum) enlisted E3 to evaluate the potential for zero-carbon hydrogen in a low-carbon future in the Western U.S. Research questions include:**
  - What are the most viable hydrogen production methods, based on expected cost trajectories?
  - What is the market outlook for hydrogen across sectors in the Western United States under a deep decarbonization future?
  - What is the potential role of hydrogen as a long-duration storage medium in a deeply decarbonized Western electricity system?
  - What does the hydrogen supply chain in the West look like today, and how may this supply chain evolve in a deep decarbonization future?
+ **The study built on existing E3 research from across the West[1], including:**
  - The development of **zero-carbon fuels**—for instance, biofuels, synthetic gas, and/or hydrogen—will be necessary to supply low-carbon energy to end uses that are not easily electrified
  - Achieving **absolute zero electricity sector emissions** is prohibitively expensive unless there is access to **zero-carbon fuels or long duration storage**, with potential emerging resources including hydrogen, advanced nuclear, long-duration energy storage, synthetic fuels or biofuels

[1]These studies include:
Deep Decarbonization in a High Renewables Future CEC-500-2018-012 (CEC, 2018)
Resource Adequacy in the Pacific Northwest (2019)
Long Run Resource Adequacy under Deep Decarbonization Pathways for California (2019)

How this study complements and differs from prior E3 research

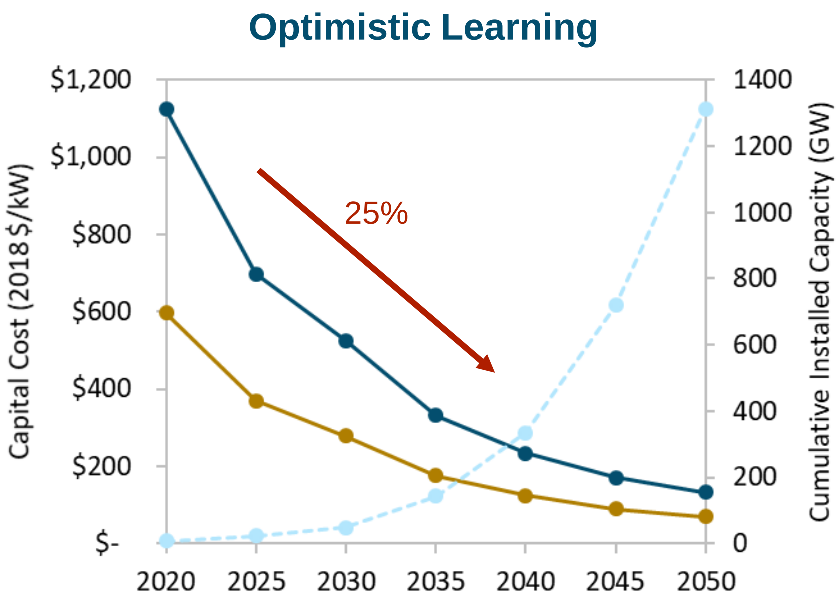
+ Electricity sector analysis

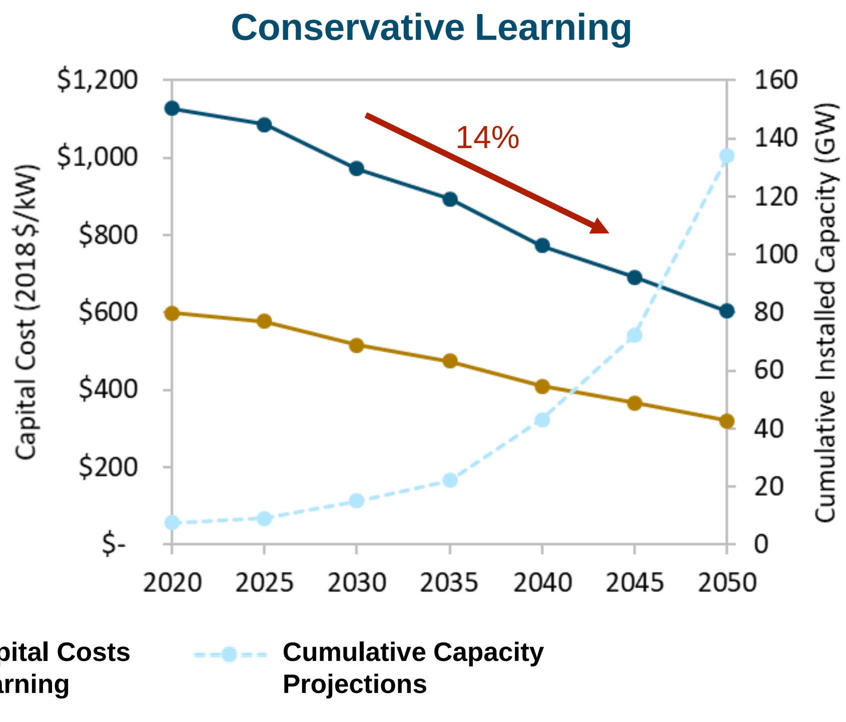
- This is the first time that E3 has performed an in-depth exploration of the potential role of hydrogen compared to lithium-ion storage, using forecasted market price dynamics
- This analysis looks at hydrogen independently, and does not attempt to compare the cost-effectiveness of hydrogen relative to alternative zero-carbon firm capacity resources, or other emerging forms of long-duration energy storage technologies

+ Hydrogen demand in other sectors using PATHWAYS scenarios

- MHPS PATHWAYS scenarios are West-wide, while E3 CEC PATHWAYS modeling is for California
- The MHPS “Mid-hydrogen” scenario is most similar to E3’s previous High Electrification scenario from the “Deep Decarbonization in a High Renewables Future” study (2018, CEC-500-2018-012), while the "High-hydrogen" scenario reflects a similar proportion of hydrogen in the economy as the CEC "High Hydrogen" scenario, but assumes hydrogen in pipelines is only used to decarbonize buildings in colder climates in the West
- The “Transformative” scenario is a new scenario designed to explore a broader set of potential market opportunities for hydrogen, in a future with lower-cost, renewable hydrogen
- These study conclusions are broadly consistent with our prior work, finding most promising end-use demands for hydrogen (outside power) in long-haul trucking and heavy-duty transportation, with more limited/speculative potential in buildings and industry. We note that the power sector findings are new to this study.

Learning Curves for Alkaline Electrolyzers



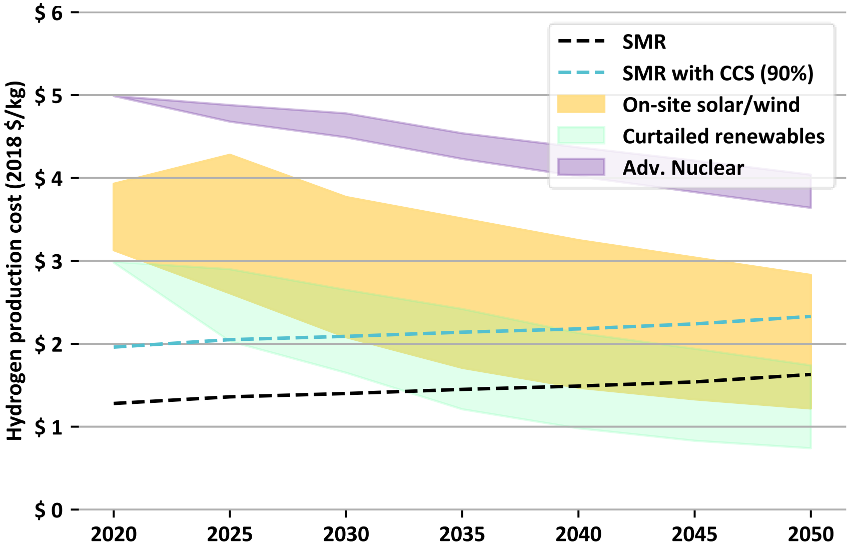


+ **"MHPS 2020 capital costs" uses 2020 capital cost data from MHPS, coupled with E3 assumptions regarding learning curves for future cost projections**
+ **E3/UCI capital cost learning curves and cumulative electrolyzer production assumptions are from E3's "Challenge of Retail Gas in California's Low-Carbon Future" study for the CEC with UC Irvine (UCI)**
+ **For comparison, solar PV modules have seen a learning rate of 22.5% from 1976 to 2016***

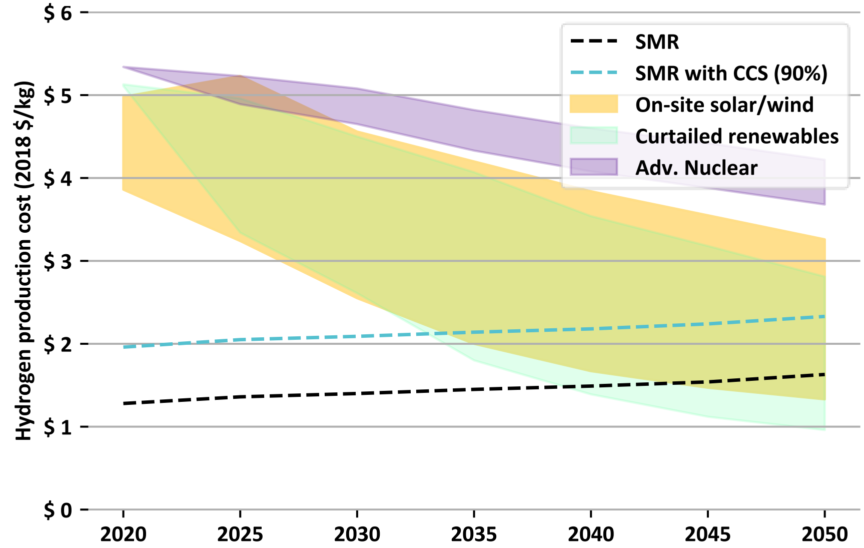
* ITRPV 2017

Hydrogen Production Costs

Using MHPS CapEx with E3/UCI Learning Curve Assumptions



Using E3/UCI CapEx and Learning Curve Assumptions



+ **Steam methane reformation (SMR) with 90% CO_2 capture from carbon capture and storage (CCS) is likely to be cheaper than electrolysis with renewable power until 2025, under MHPS cost assumptions and until early 2030s under E3/UCI cost assumptions**
  - A stringent cap/price on carbon emissions forcing close to 100% CO_2 capture on CCS may hurt SMR + CCS economics, and process may require additional direct air capture of carbon dioxide, or biogas blend to offset remaining emissions
+ **Electrolysis with renewable power may be more economic than SMR + 90% CCS by 2025 if:**
  - Electrolyzer costs, currently assumed at $597/kW, fall with an aggressive learning rate of 25%
  - Curtailed renewables are available at close to zero cost and an electrolyzer utilization of at least 15%* can be attained using the same
+ **The most economic way of producing hydrogen in the long run is uncertain**

* Uncertainty band for cost projections from curtailed renewables in the graph is for a utilization rate of 15%

Power sector modeling approach shows significant opportunity for hydrogen as long-duration storage

+ E3 performed two analyses to assess opportunities for hydrogen in the power sector

E3 AURORA
Hourly Market Price & System Dispatch Forecast

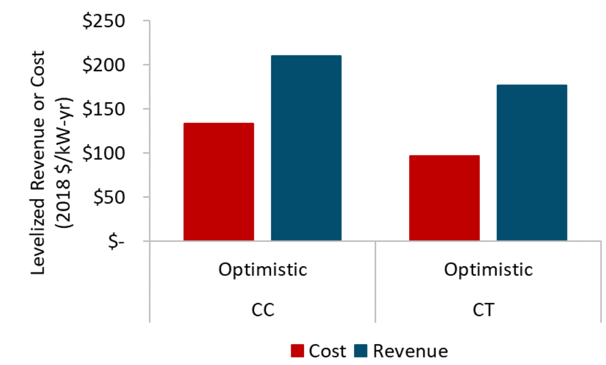
1 Potential "First-Mover" Hydrogen Storage Revenue

E3 RESTORE
Power sector model of optimal storage dispatch based on E3's High RPS* scenario for the West

Levelized Revenues

MHPS Levelized Costs

Potential Power Sector Revenue & Cost CA ($/kW-yr) 2045



2 Potentially Economic Hydrogen from Curtailed Power

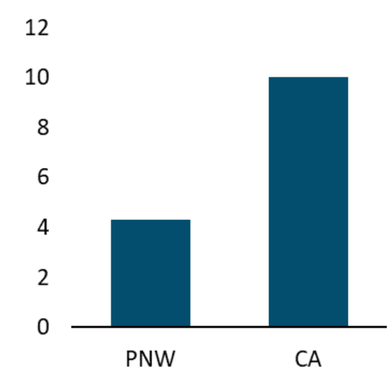
E3 RESTORE
Hourly operations results

E3 Equilibrium Model

Economic Market Size

MHPS Levelized Costs

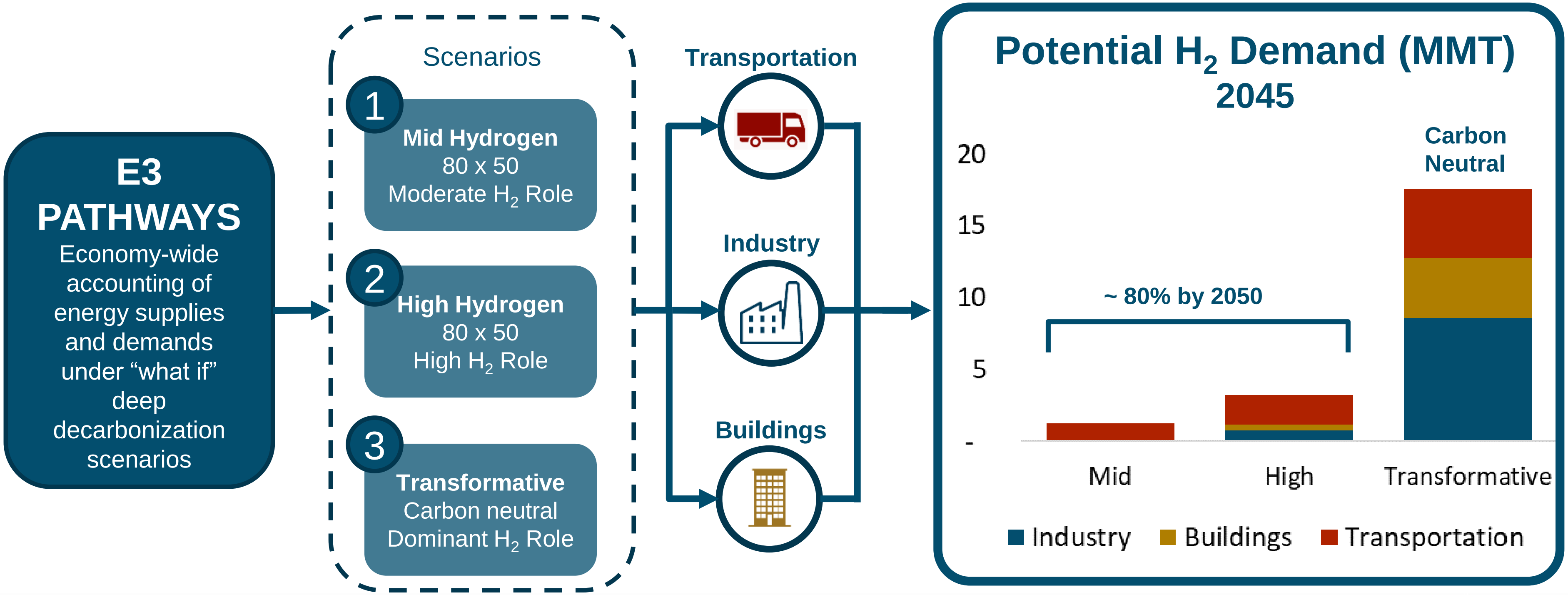
Potential H_2 Power Storage Market (GW) 2045



* RPS refers to Renewable Portfolio Standard.

Economy-wide modeling suggests broad hydrogen demand most likely in a carbon-neutral future

- **Hydrogen demand under a carbon-neutral future is very high, but requires infrastructure investments and competing with electrification**
- **Hydrogen could decarbonize certain applications in critical sectors**
  - Trucking: Hydrogen fuel cell trucking is characterized by fast fueling times and lower weight, enabling greater carrying capacity than battery alternatives
  - Industrial: Natural gas replaced with hydrogen for some high temperature and thermochemical processes that are ill-suited for electrification

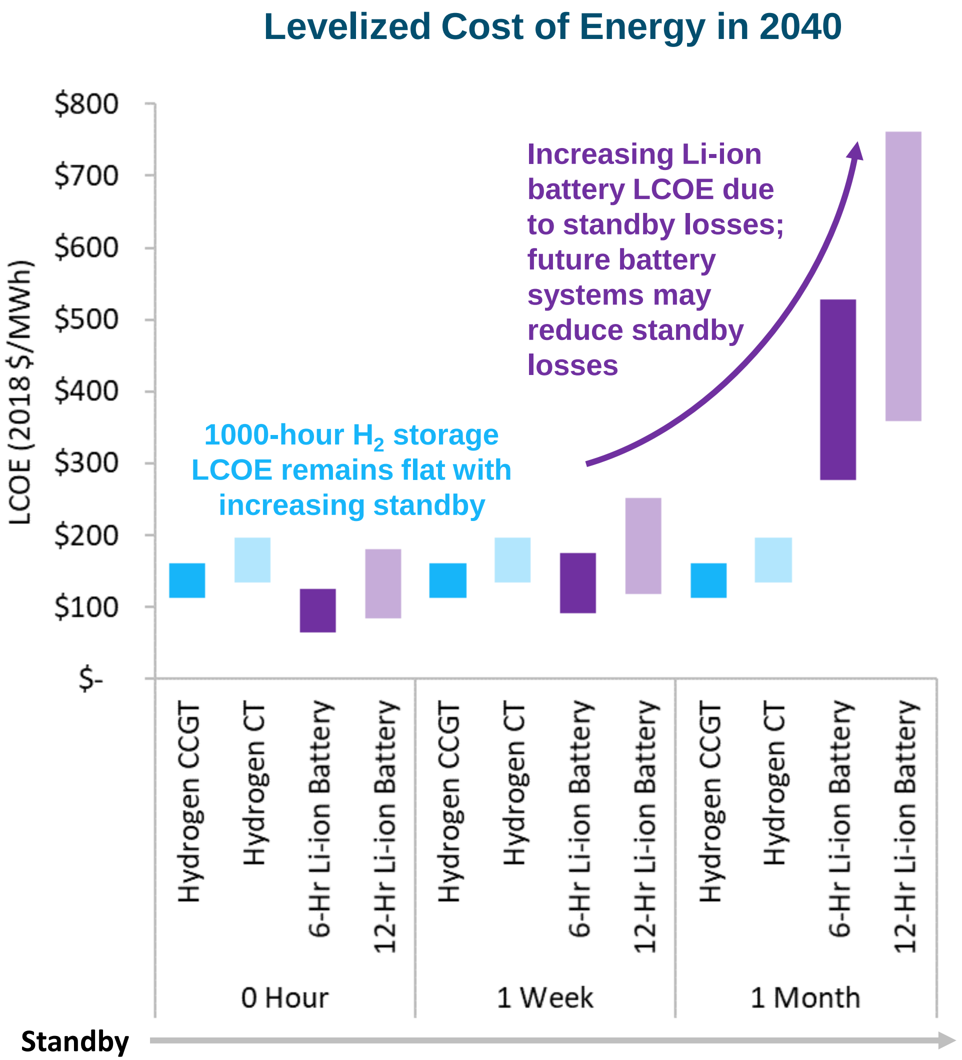


Key Project Takeaways

+ **The most promising opportunity for carbon-neutral hydrogen is as long-duration energy storage for the electricity sector**
  - Hydrogen market in California estimated at up to 10 GW by 2045, and in the Pacific Northwest at ~4 GW in 2045, assuming no other firm zero-carbon resources, and only storage alternatives are lithium ion batteries and pumped hydro
+ **Carbon-neutral hydrogen could play a role in decarbonizing other hard-to-electrify sectors of the economy, particularly heavy-duty ground transportation**
+ **Carbon-neutral hydrogen's role is uncertain in buildings and industry, with potential opportunities foreseeable if the Western U.S. achieves carbon targets close to complete decarbonization**
+ **The most economic means of producing carbon-neutral hydrogen in the long run remains uncertain**
  - "Blue" hydrogen (hydrogen produced from natural gas plus carbon capture and sequestration) is lower cost in early 2020s, while "green" hydrogen (hydrogen produced from renewable electricity) is competitive by the 2030s
+ **Green hydrogen production in locations with on-site, underground storage is currently lower cost than distributed production and storage of green hydrogen; Use of underground storage could serve as a cost-effective energy "hub," providing hydrogen to locations without underground storage**

Hydrogen Production Cost and Levelized Cost of Energy

Hydrogen storage is more feasible for inter-day energy shifting than Li-ion batteries



While batteries experience hourly standby losses, storing hydrogen for days, weeks and months generates minimal losses – thus enabling inter-day and seasonal energy shifting

+ **Hydrogen storage key assumptions**
  - Ratio of solar resource (MW) to CT/CCGT (MW) is 2.5 to 1, based on MHPS input (i.e., 2.5 MW of solar and electrolyzer for 1 MW of CT/CCGT, implying a capacity factor of about 30%–40%)
  - LCOE range represents E3 and MHPS electrolyzer costs
+ **Li-ion battery key assumptions**
  - Ratio of solar resource (MW) to Li-battery (MW) is 1 to 1 (i.e. 1 MW solar to 1 MW battery)
  - Approximate daily cycling, with excess solar sold to grid at $20/MWh
  - Battery standby loss = 0.2% per hour
  - LCOE range represents battery costs in E3 Pro Forma model
+ **Both estimates assume 2040 costs and Utah solar**

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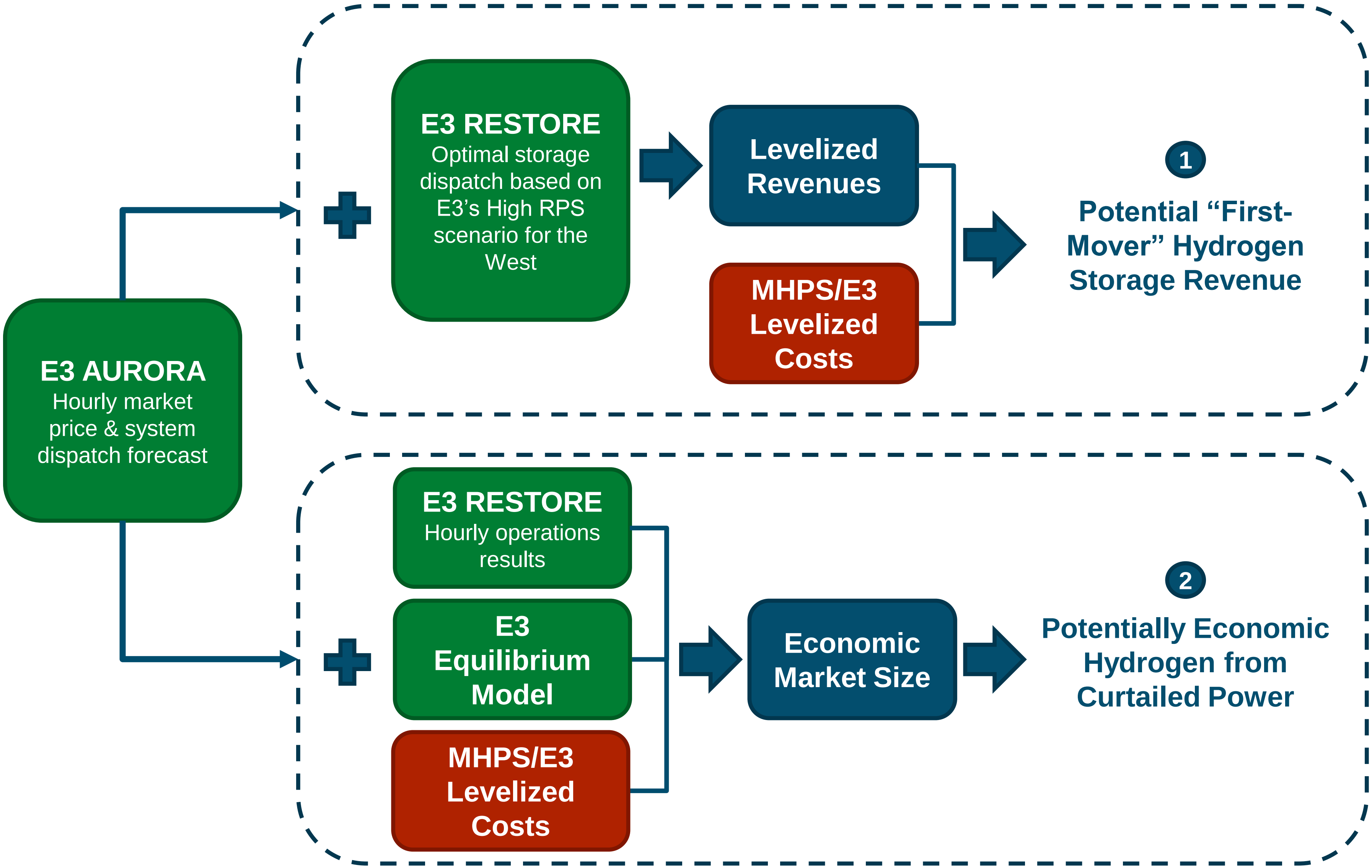
Hydrogen Outlook in the Power Sector

RESTORE and Market Equilibrium Modeling

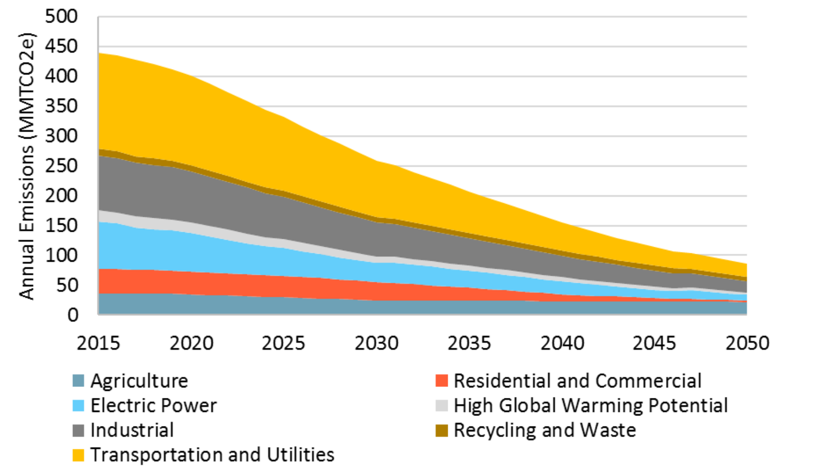
E3 power analyses suggest opportunity for hydrogen in WECC power sector



Context: CA market outlook reflects stringent decarbonization targets (SB 100)

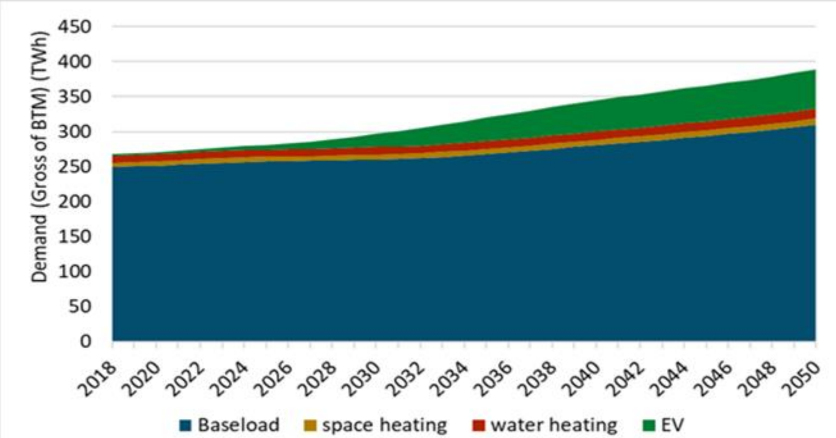
+ **Clean energy policy dominates future electric loads and generation trends**
  - SB 100 mandates 100% carbon-free (as % of retail sales) by 2045
  - Load growth in near term will be moderated by continued growth in behind-the-meter (BTM) solar and energy efficiency
  - Greenhouse gas (GHG) targets likely to drive increasing building and transportation electric loads
+ **Gas plant retirements are impacting the state's capacity needs**
  - Driven by once-through cooling policy, declining energy market revenues, and increasing competitiveness of battery storage

California GHG Emissions Reduction Targets



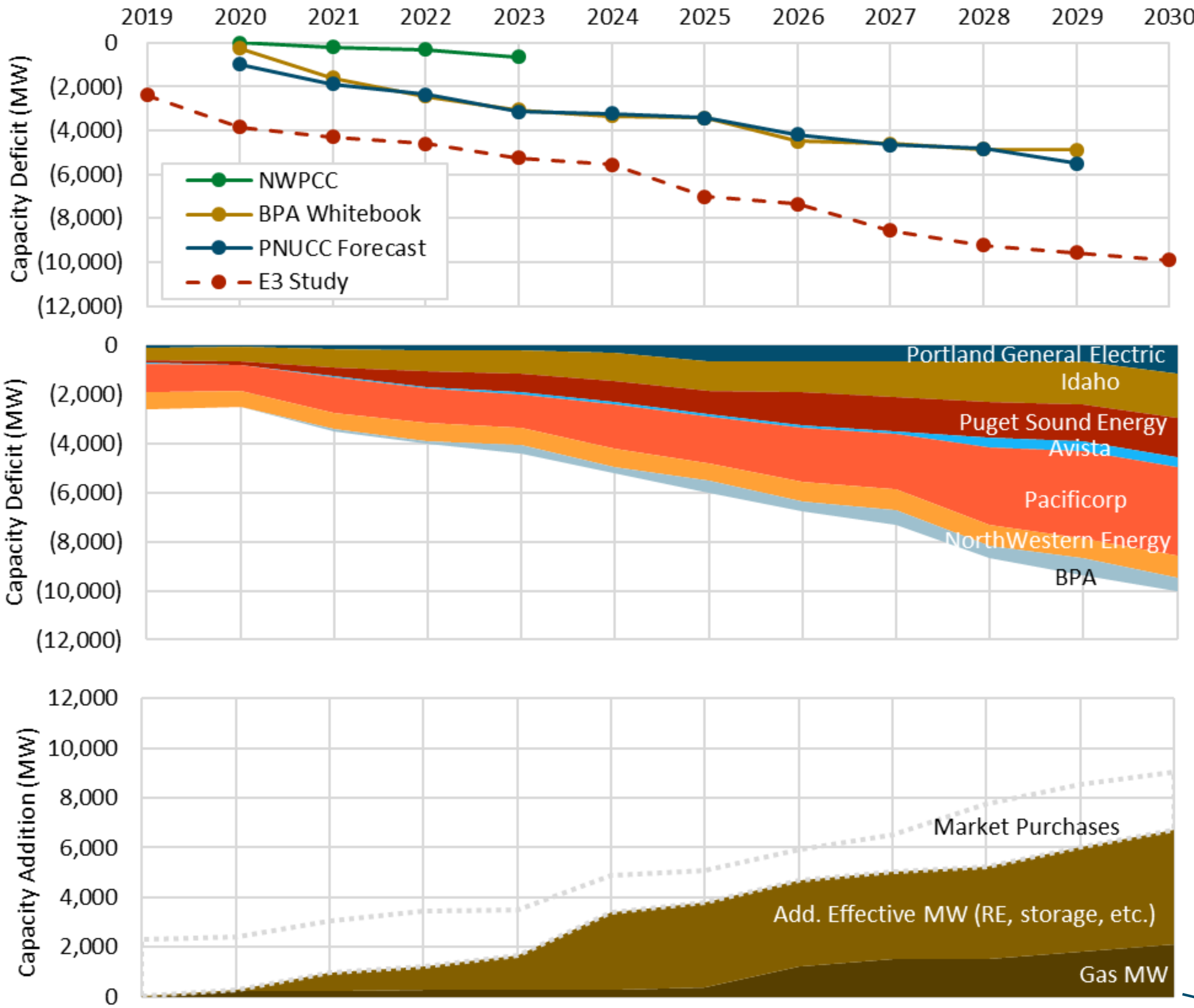
Source: E3 PATHWAYS analysis for 80% GHG reduction by 2050. (Note: both SB100 and GHG goals may allow small levels of emissions to remain in the electric sector by 2050.)

California Electric Loads in E3 Aurora High RPS Case



Source: E3 Aurora High RPS Scenario.

Context: Existing E3 work demonstrates PNW near-term capacity needs in excess of planned additions



"Top-Down" Regional Assessments

6,000 – 10,000 MW capacity need by 2030

"Bottom-Up" Review of Utility IRPs

10,000 MW capacity need by 2030

IRP Planned Resource Additions

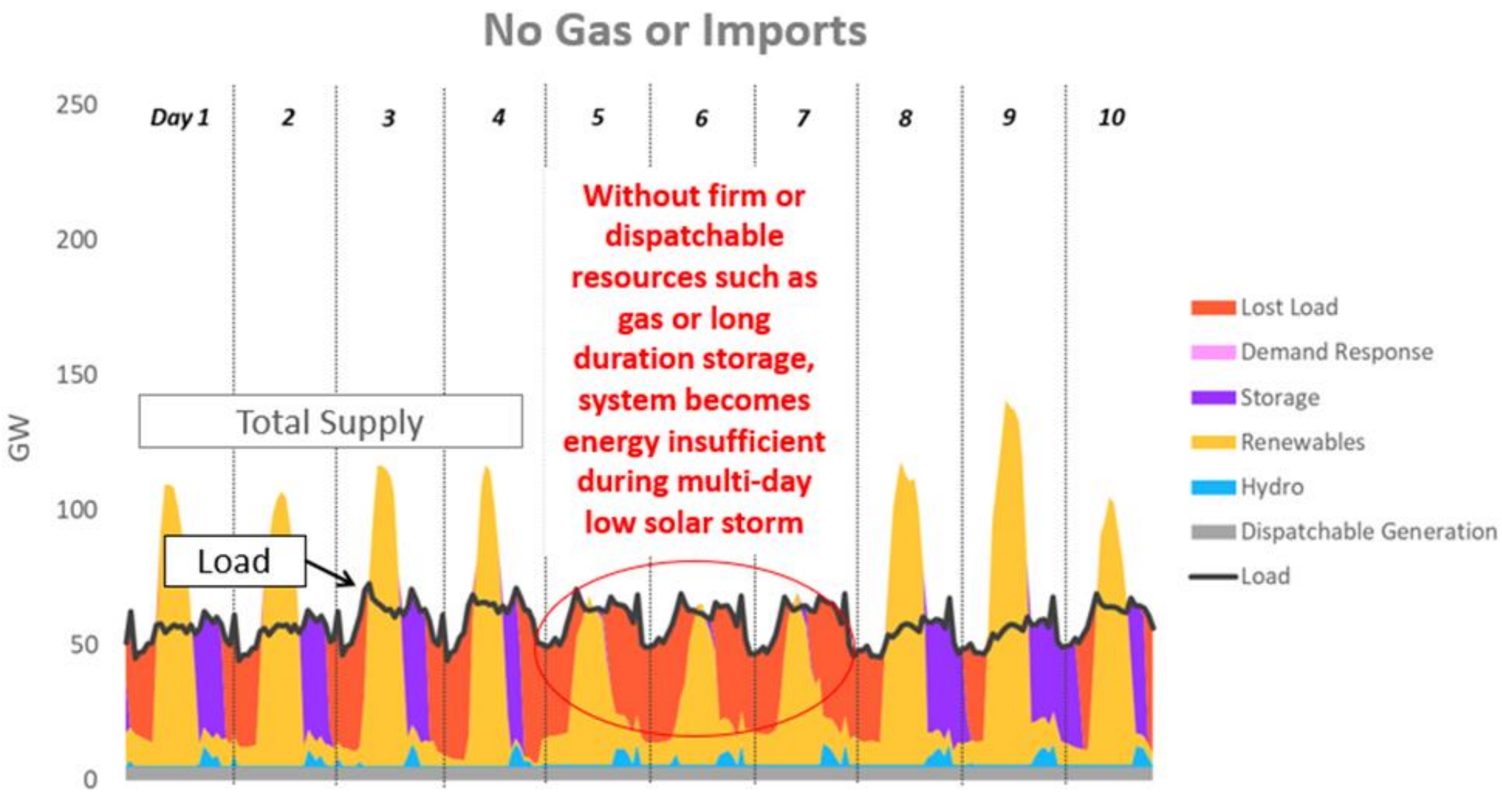
Only 4,600 MW effective capacity additions…
2,300 MW of market purchases do not address regional need

~1,500 MW of 2,000 MW firm gas capacity is proposed by OR/WA utilities that may face political opposition

Finding from E3's December 2019 study, *Capacity Needs of the Pacific Northwest-2019 to 2030*.

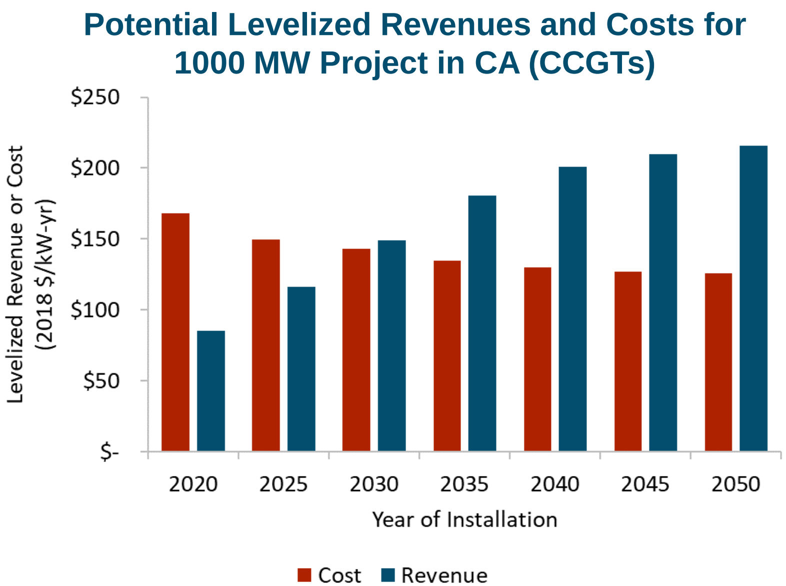
Dispatchable generation enables the system to ride out *dunkelflaute* conditions

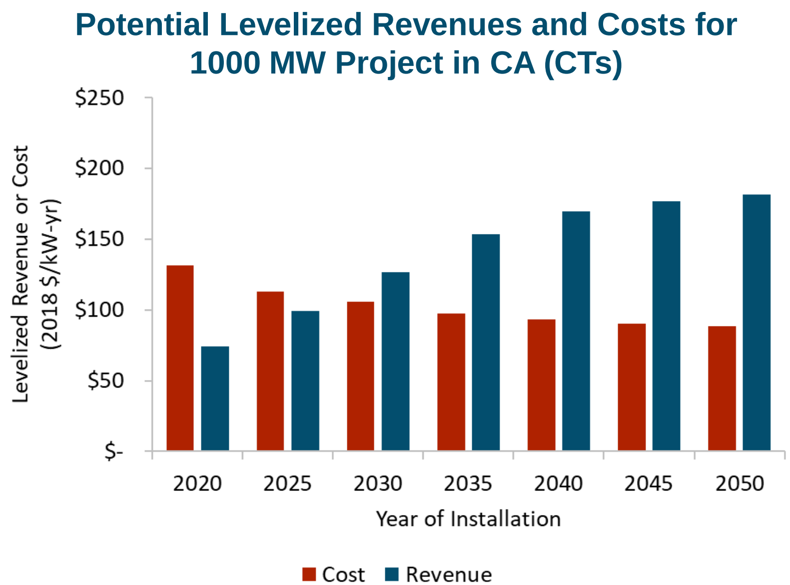
- **Dispatchable generation can help prevent loss-of-load during multi-day low renewable output stretches in the West**
- **In 80x50 future, natural gas continues to provide cheapest reliability resource, but other firm carbon-free resources would be needed to get to a zero-carbon grid**
  - Hydrogen, fossil + carbon capture and storage, nuclear are all options



Price Taker Model: First-mover hydrogen projects have potential to earn significant revenues

+ **E3 relied on our optimal storage dispatch model (RESTORE) to estimate potential revenues for a 1000 MW hydrogen storage project in the California market**
  - Price-taker model with perfect foresight
+ **Gas plants operating on 100% hydrogen constructed in 2030 and beyond have levelized revenues higher than costs**
  - Costs based on MHPS initial costs and E3 optimistic learning curves
  - Revenues reflect differential between grid charging cost and energy discharge revenues, and assume both energy and capacity market revenues
  - CTs even more profitable given lower costs more than compensate for lower revenues



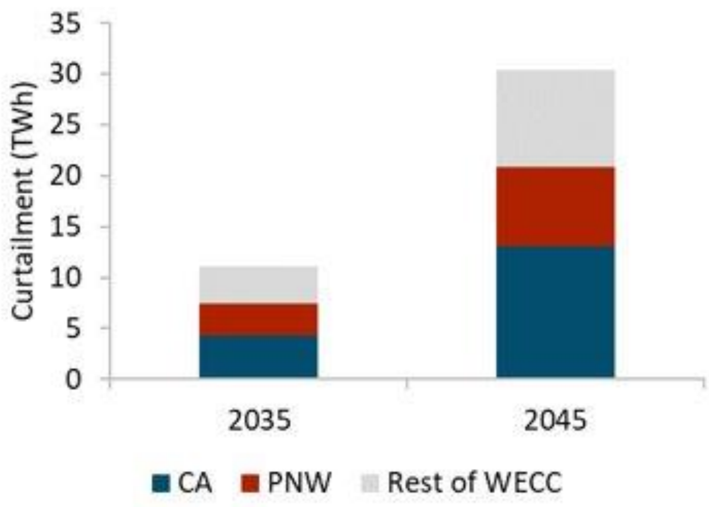


Equilibrium Market Size: E3 developed model to evaluate economic hydrogen potential in the West

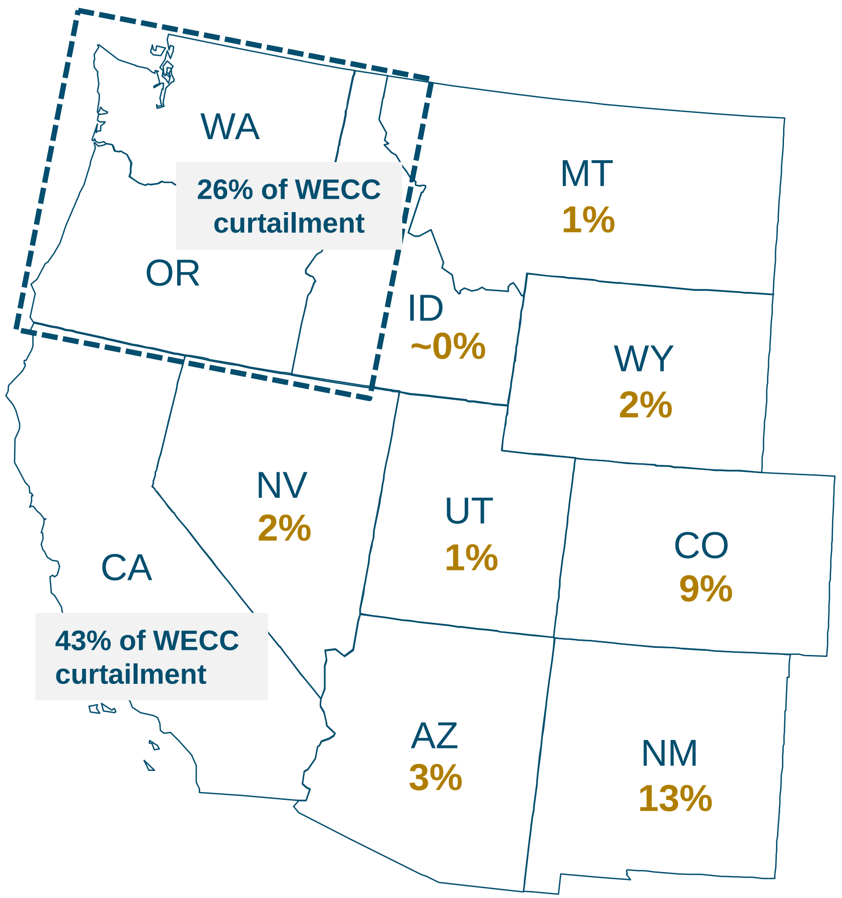
+ **Today:** **Demand for long-duration storage in the power market is currently fulfilled by firm resources (largely natural gas power plants)**
+ **Future:** **Demand will be driven by climate policy, firm capacity needs, and technology cost-competitiveness**
  - Zero-carbon resources like hydrogen may play important role as dispatchable resource
+ **Market equilibrium model:** **Estimates market size based on economics**
  - Logic for charging/discharging and updating market prices based on existing market dynamics
  - Hydrogen generation assumed to be from curtailed power (zero- or negative-priced energy), but potential greater opportunities from off-grid renewables (not included in the equilibrium model given model limitations)
  - Price and curtailment data assume significant batteries in place for load and resource balance, implying greater opportunities for long-duration storage if early market entry possible
  - Results based on E3's Aurora High RPS Market Price scenario (more info in Appendix)
+ **Region:** **Focus on California and Pacific Northwest as first markets due to higher availability of curtailed power**
  - Results sensitive to both market conditions and technology characteristics (costs and efficiency)

E3's High RPS scenario modeling finds most curtailment will be in CA and PNW

+ **In E3's Aurora High RPS scenario, California and the Pacific Northwest collectively account for:**
  - 67% WECC-wide curtailment in 2035
  - 69% of WECC-wide curtailment in 2045



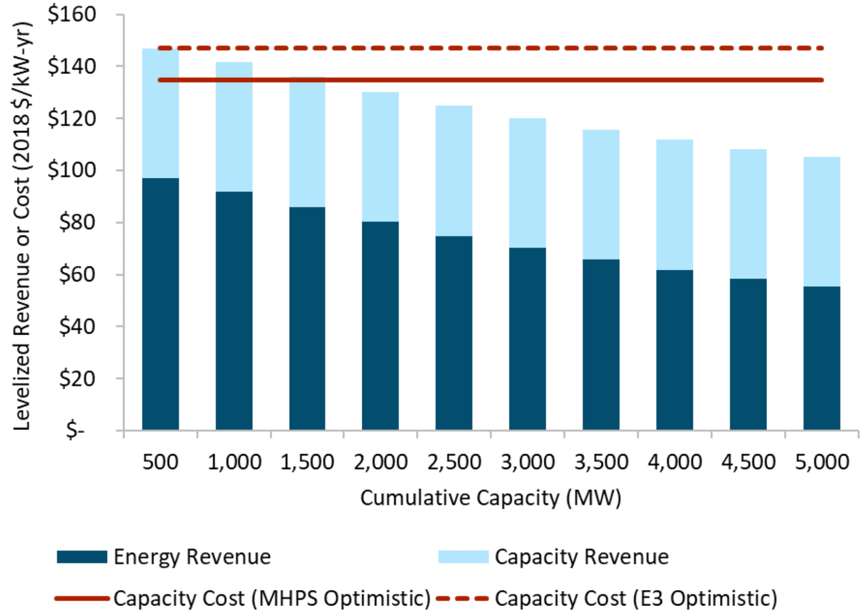
2045 State-by-State Curtailment as Percent of Total WECC Curtailment in Aurora High RPS Scenario



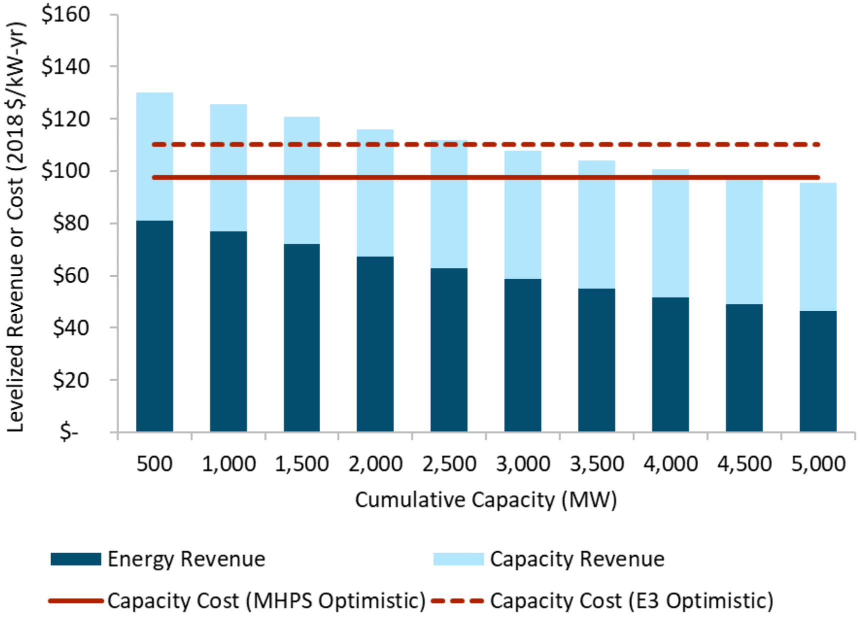
*Not shown: British Columbia (1%), Alberta (~0%), North Baja CA (1%). Rounded percentages thus not exactly 100%.

Potential CA Market Hydrogen Penetration
2035 electrolyzer and curtailed electricity only

Levelized H_2 Revenue and Costs vs. Market Penetration (CCGT, 2035 Vintage, California, Market Equilibrium)



Levelized H_2 Revenue and Costs vs. Market Penetration (CT, 2035 Vintage, California, Market Equilibrium)

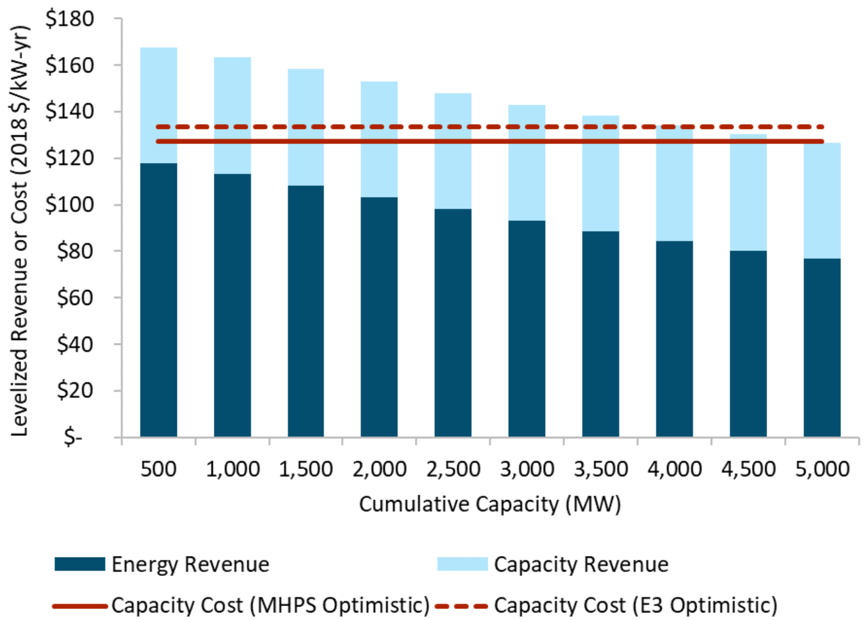


E3 used Aurora Market Price forecasts for the High RPS case in California to estimate up to 1.5 GW profitable P2G* + CCGT market size or around 2.5 to 4.5 GW profitable P2G + CT market size in 2035

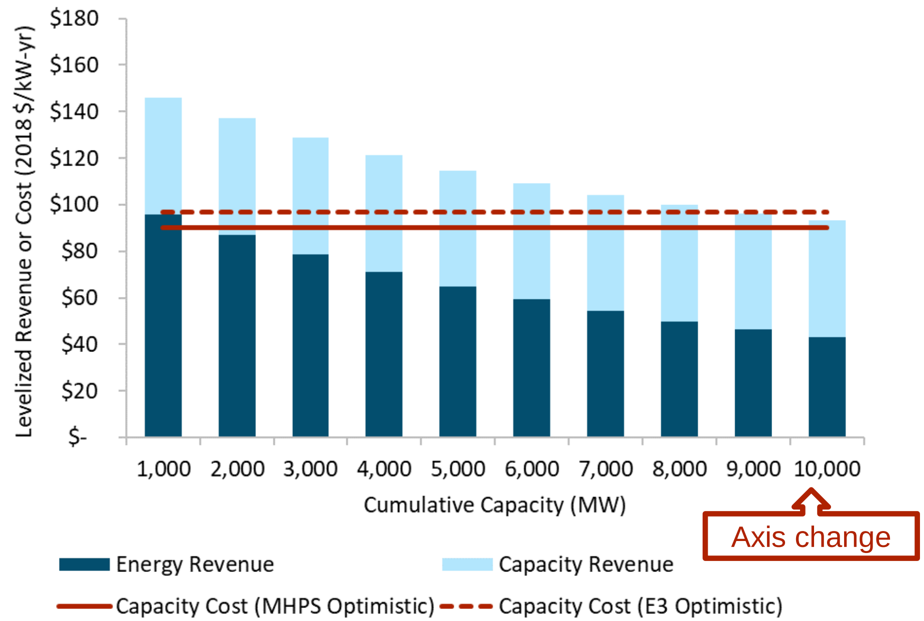
* P2G refers to power-to-gas.

Potential CA Market Hydrogen Penetration
2045 electrolyzer and curtailed electricity only

Levelized H_2 Revenue and Costs vs. Market Penetration (CCGT, 2045 Vintage, California, Market Equilibrium)



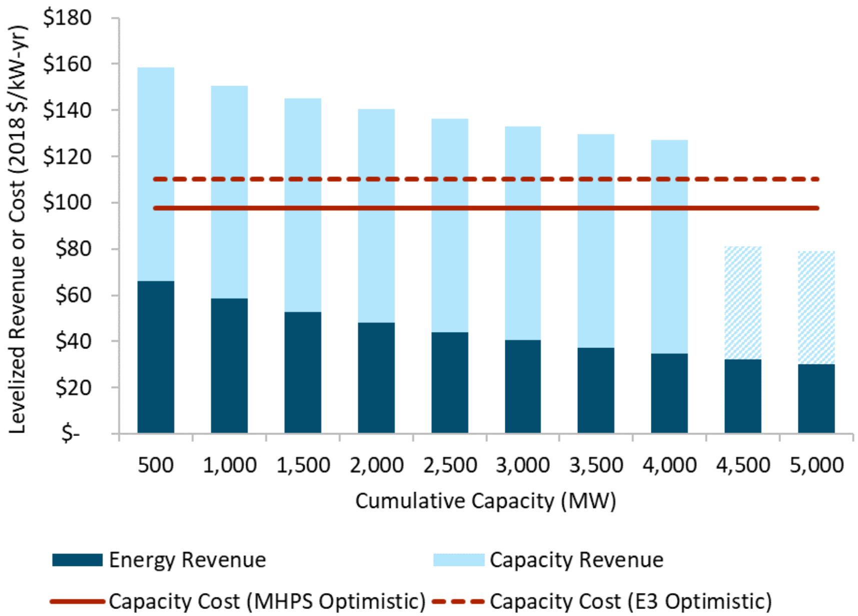
Levelized H_2 Revenue and Costs vs. Market Penetration (CT, 2045 Vintage, California, Market Equilibrium)



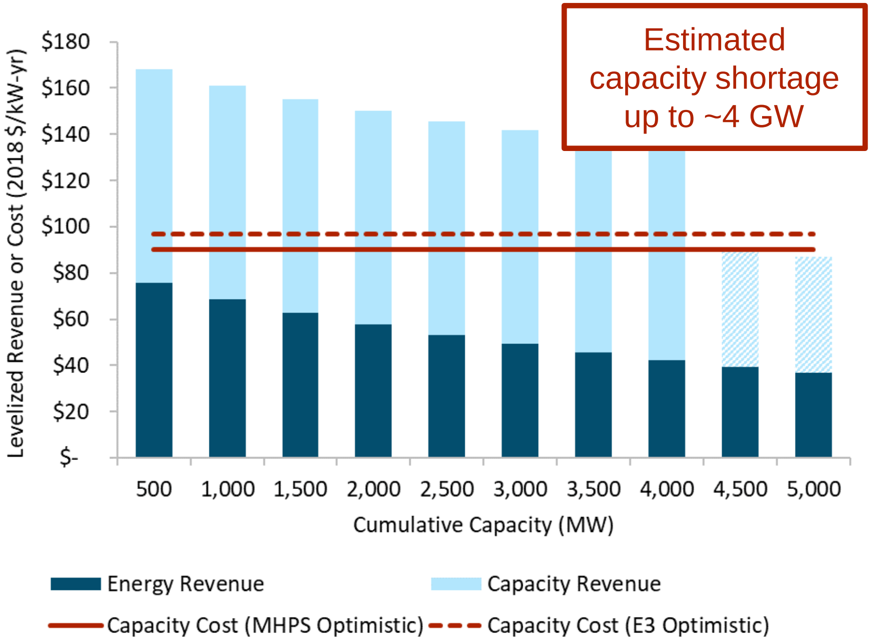
E3 used Aurora Market Price forecasts for High RPS case in California to estimate up to 5 GW profitable P2G + CCGT market size or up to 10 GW profitable P2G + CT market size in 2045

Potential PNW Market Penetration
electrolyzer and CTs, curtailed electricity only

Levelized H_2 Revenue and Costs vs. Market Penetration (CT, 2035 Vintage, Pacific NW, Market Equilibrium)



Levelized H_2 Revenue and Costs vs. Market Penetration (CT, 2045 Vintage, Pacific NW, Market Equilibrium)



E3 used Aurora Market Price forecasts for High RPS case in PNW to estimate ~4 GW profitable P2G + CT market size in 2035 and 2045

* P2G refers to power-to-gas.

Key Uncertainties in Market Outlook Estimates

- **Carbon constraints:** This study does not use a 100% decarbonized grid. In a fully carbon constrained future, the remaining natural gas generation (around 12% of annual generation) would need to be replaced with dispatchable storage or another zero-carbon firm resource. This could **increase** demand for hydrogen.
- **Capacity prices:** Market viability of hydrogen long-duration storage relies on substantial capacity payments in all cases, which are uncertain and driven by capacity needs in the Pacific Northwest and California. We assume gas CTs and CCGTs provide capacity, but if other resources are on the margin for providing capacity, this could **increase** or **decrease** the viability of hydrogen.
- **Amount of Li-Ion build:** The amount of curtailed power for hydrogen production was estimated in a future where there is already significant battery build. If hydrogen can beat batteries to market, hydrogen's viability may **increase**.
- **Economic hydrogen dispatch from off-grid renewables:** Additional economic hydrogen build could rely on non-curtailed grid power or off-grid renewables and compete economically in the market. This may **increase** hydrogen's viability.
- **Other emerging technologies:** This study did not consider other emerging technologies that could compete with hydrogen (e.g., new forms of chemical battery storage, advanced nuclear, compressed air energy storage, etc.) and **decrease** the market share captured by hydrogen.

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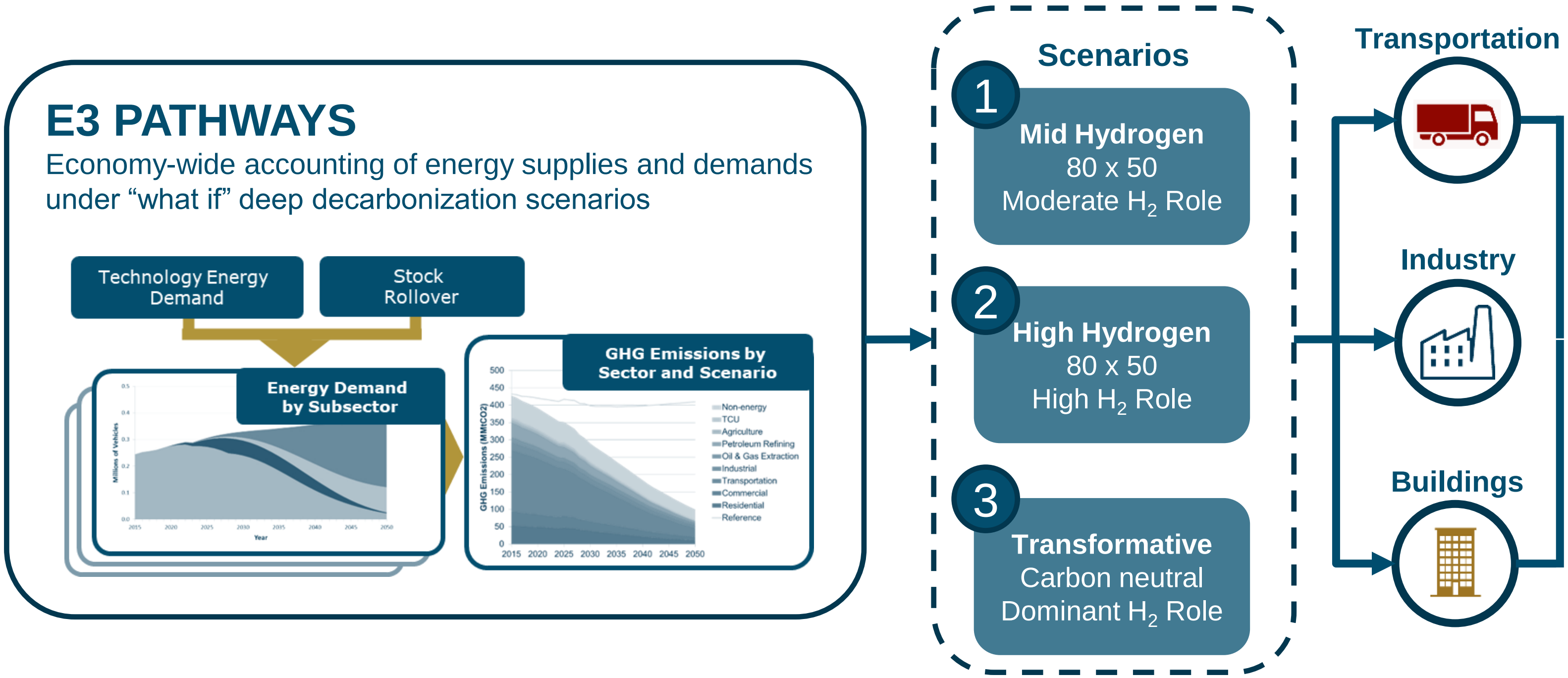
Hydrogen Outlook in Buildings, Transportation and Industry

PATHWAYS Modeling

PATHWAYS scenarios reflect potential opportunities for hydrogen in the West

+ **E3's PATHWAYS model is an economy-wide infrastructure-based GHG scenario analysis driven by user-defined scenarios (i.e., not an optimization)**
+ **E3 constructed three PATHWAYS scenarios for the West to reflect plausible future opportunities for hydrogen across the economy**
  - Model regions based on U.S. Census, with West represented by "Pacific" and "Mountain" regions
  - Scenarios consistent with increasingly stringent economy-wide GHG mitigation scenarios



Hydrogen demand in E3's PATHWAYS modeling is most likely under carbon neutral futures

Scenarios reflect increasing hydrogen reliance

Sector	Mid-Hydrogen	High-Hydrogen	Transformative	
Carbon Target	80 x 50	80 x 50	Carbon Neutral	
Passenger Vehicles	2025 2045	 2025 2045	 2025 2045	% HFCV* sales
Heavy Duty Vehicles	 2025 2045	 2025 2045	 2025 2045	% HFCV sales
Buildings	2025 2045	 2025 2045	 2025 2045	% H_2 in total sector energy demand
Industry	2025 2045	 2025 2045	 2025 2045	% H_2 in total sector energy demand

* HFCV refers to hydrogen fuel cell vehicle.

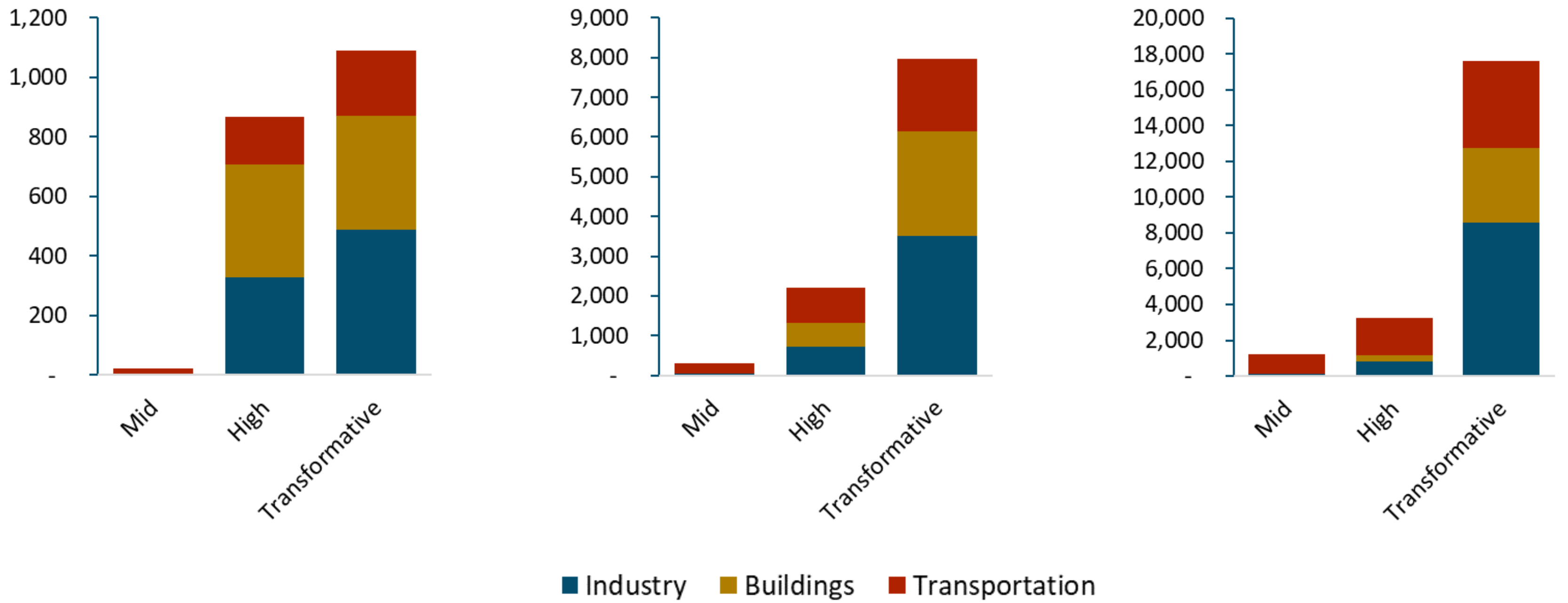
Zero Carbon Hydrogen Demand by Sector and Scenario Over Time

+ **Total estimated hydrogen demand in the short, medium, and long term in the West under the three PATHWAYS modeling scenarios**

Near Term Hydrogen (TMT) 2025

Medium Term Hydrogen (TMT) 2035

Long Term Hydrogen (TMT) 2045



TMT = Thousand Metric Tons

Note: Axis changes across timeframes

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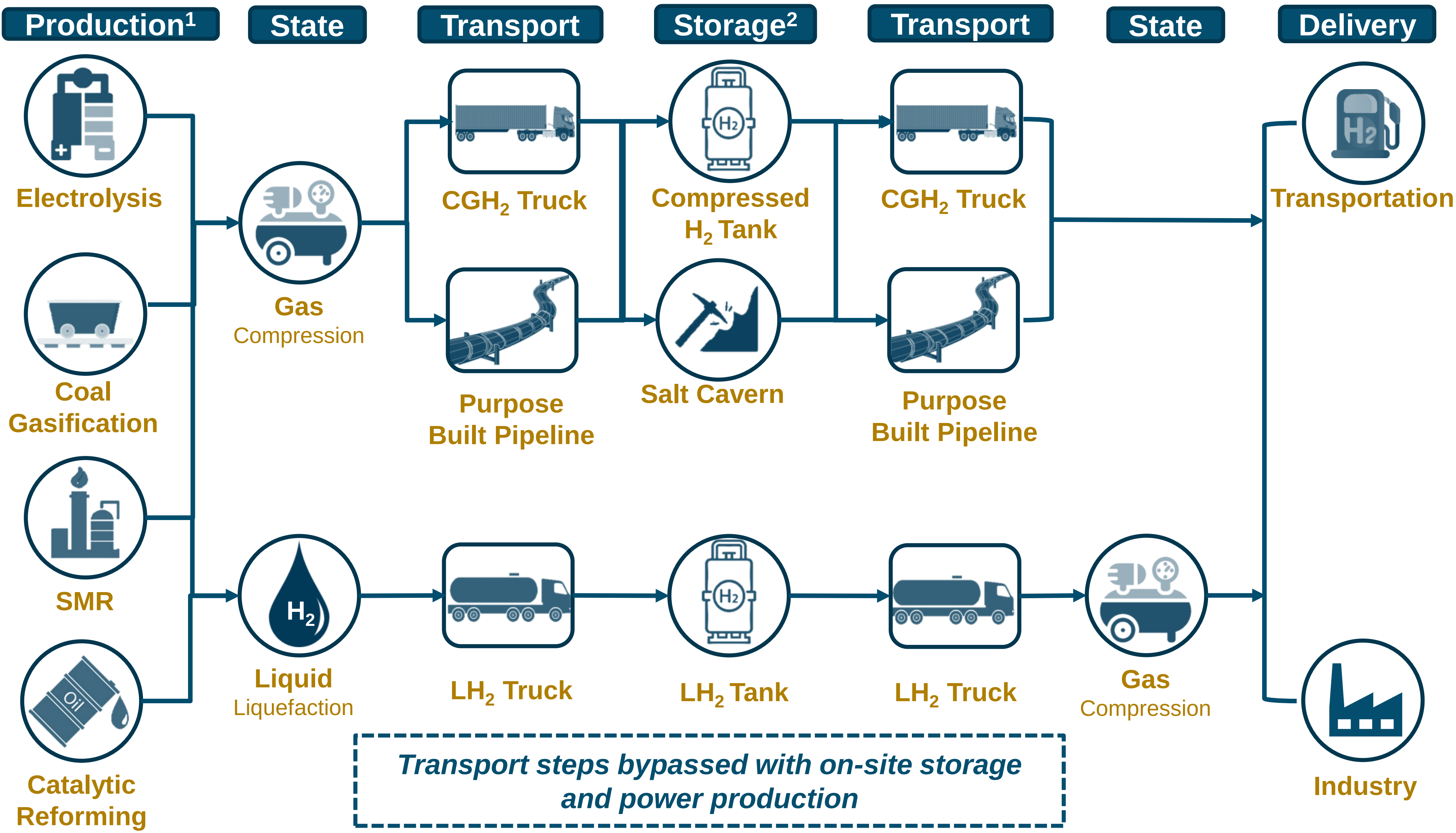
Supply Chain Overview

Current hydrogen market supply chain viable in WECC



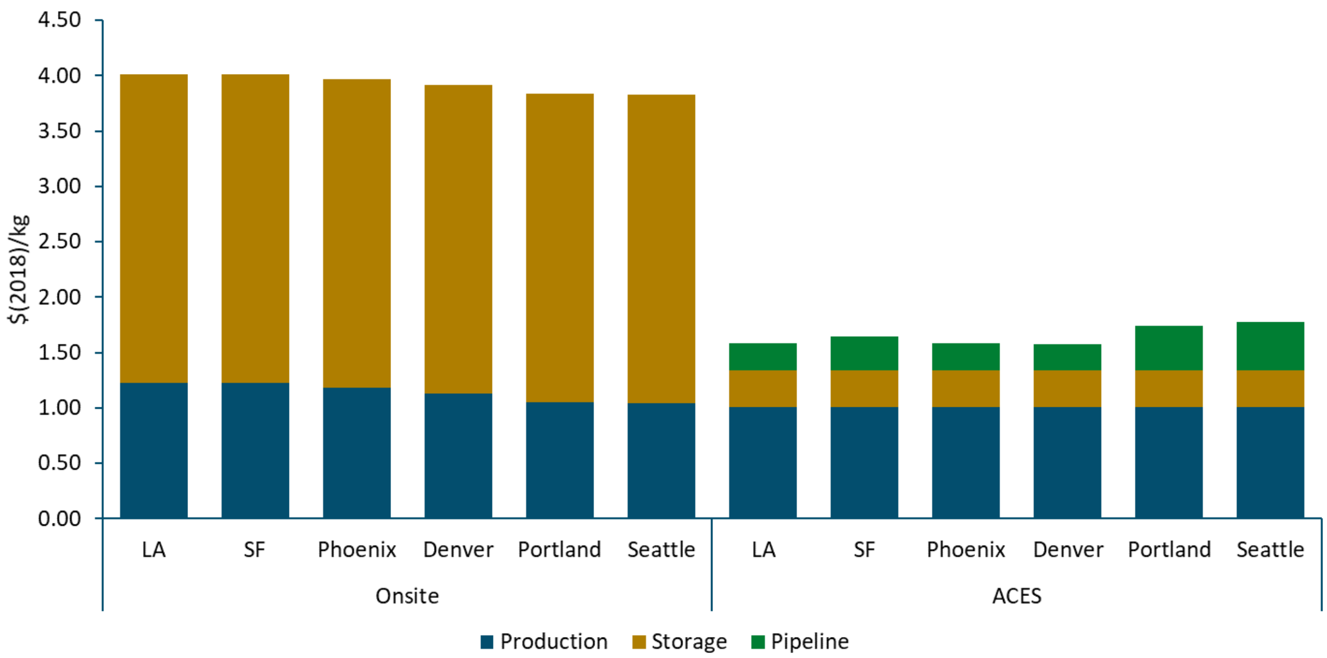
[1] Includes the most common forms of production methods today

[2] Hydrogen can be stored through other means such as ammonia and metal hydrides. This overview includes most commonly used storage technologies.

"Hub and Spoke" model may be more viable in decarbonized future

- **A hydrogen supply chain with a cheap, large-scale central hub of storage that can be piped to different areas is likely to be more cost effective than on-site, distributed production and storage**
  - It is cheaper to store hydrogen at scale in salt caverns or other geologic means than on-site in smaller high-pressure tanks (the other widely commercially available storage technology)

Potential Delivered Levelized Hydrogen Costs ($2018/kg) in 2040



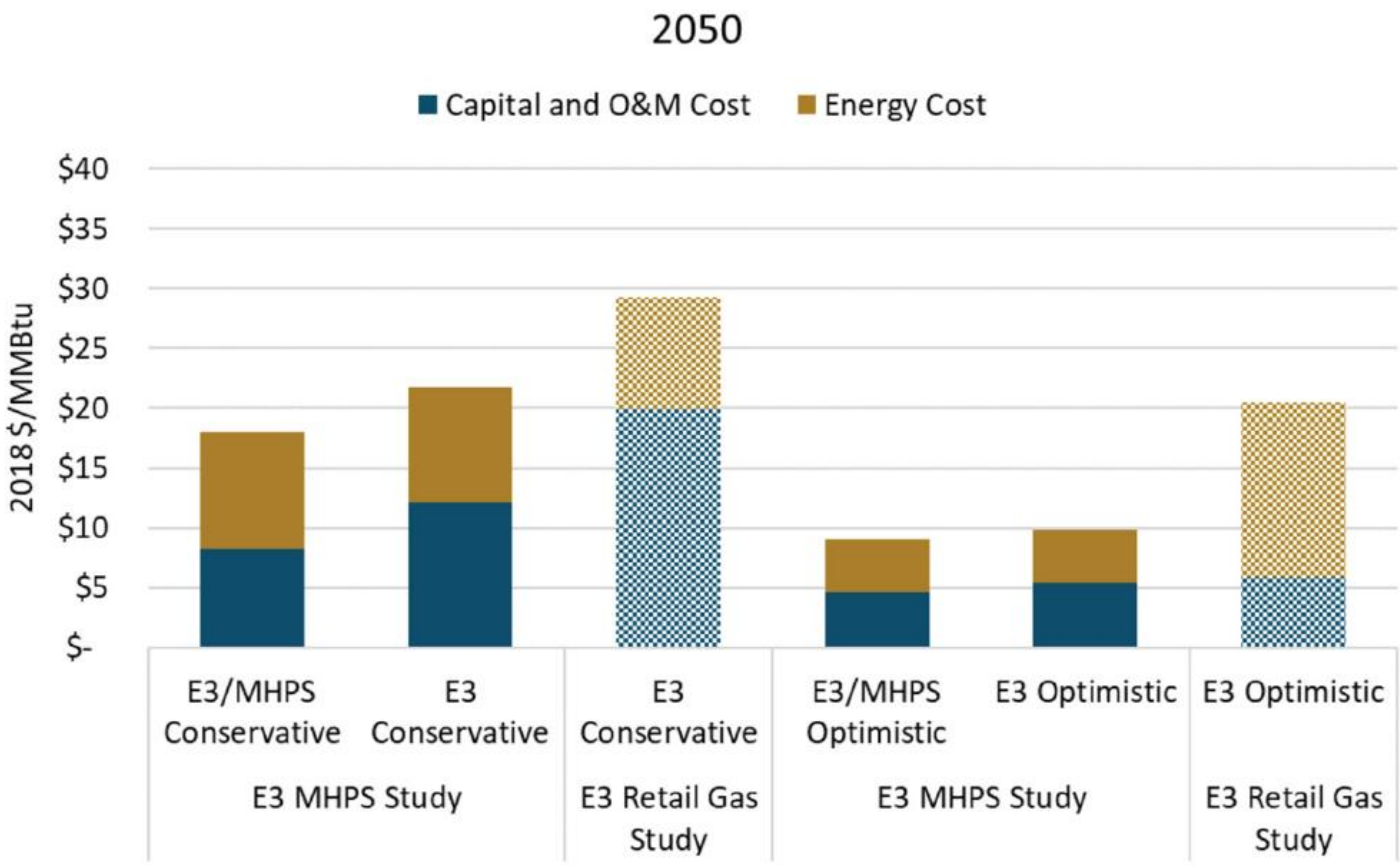
Assumptions:

- Compares cost of producing hydrogen from off-grid solar on-site (typical state solar capacity factor + state capital cost multipliers) or at the ACES site (UT solar + capital cost multiplier)
- On-site storage assumes same level of hydrogen storage as the salt cavern in Delta, UT but in compressed tanks
- Transportation only includes transmission pipeline from the ACES site following major existing gas transmission routes
- Hydrogen production cost based on MHPS estimates

Appendix

Comparison of CEC and MHPS Study Hydrogen LCOE

+ **Main driver for energy cost difference in 2050: off-grid Midwest wind cost (CEC) ~ 2-3x off-grid UT solar cost (MHPS)**

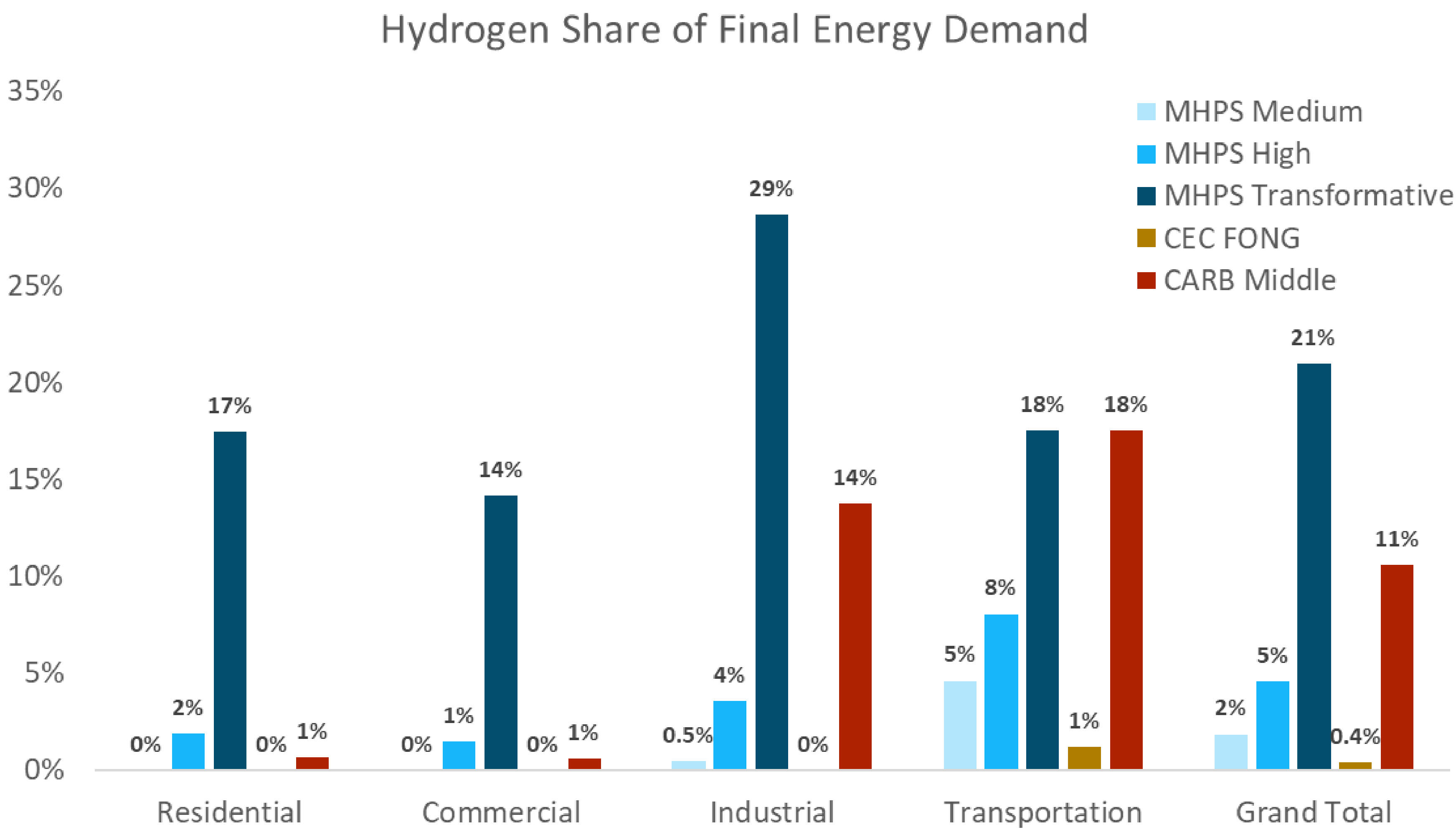


PATHWAYS Study Comparison

Sector	Measure	MHPS Medium H_2	MHPS High H_2	MHPS Transformative H_2	CEC FONG	CARB Balanced*
All	Economy-Wide Emissions Target (% reduction by 2050)	~80%	~80%	~80%	80%	100%
Buildings	Building Electrification (HP stock share)	91%	33%	33%	85%	85%
Transport-ation	LDV BEV (Stock Share)	87%	81%	49%	93%	83%
	MDV BEV (Stock Share)	83%	83%	25%	33%	89%
	HDV BEV (Stock Share)	41%	10%	0%	27%	40%
	LDV FCEV (Stock Share)	0%	13%	45%	3%	3%
	MDV FCEV (Stock Share)	0%	0%	59%	0%	0%
	HDV FCEV (Stock Share)	46%	48%	66%	52%	43%
Industry	Industry EE (% reduction in final energy demand from EE)	25%	25%	25%	None	10%
	Industry Electrification (% of gas demand electrified)	5%	5%	5%	None	36%
Electricity	Carbon-Free Generation Share	~77% WECC-wide by 2050 from separate analysis (Aurora)**			95%	100%
Hydrogen	H_2 Share of Final Energy Consumption	2%	5%	21%	0.4%	11%

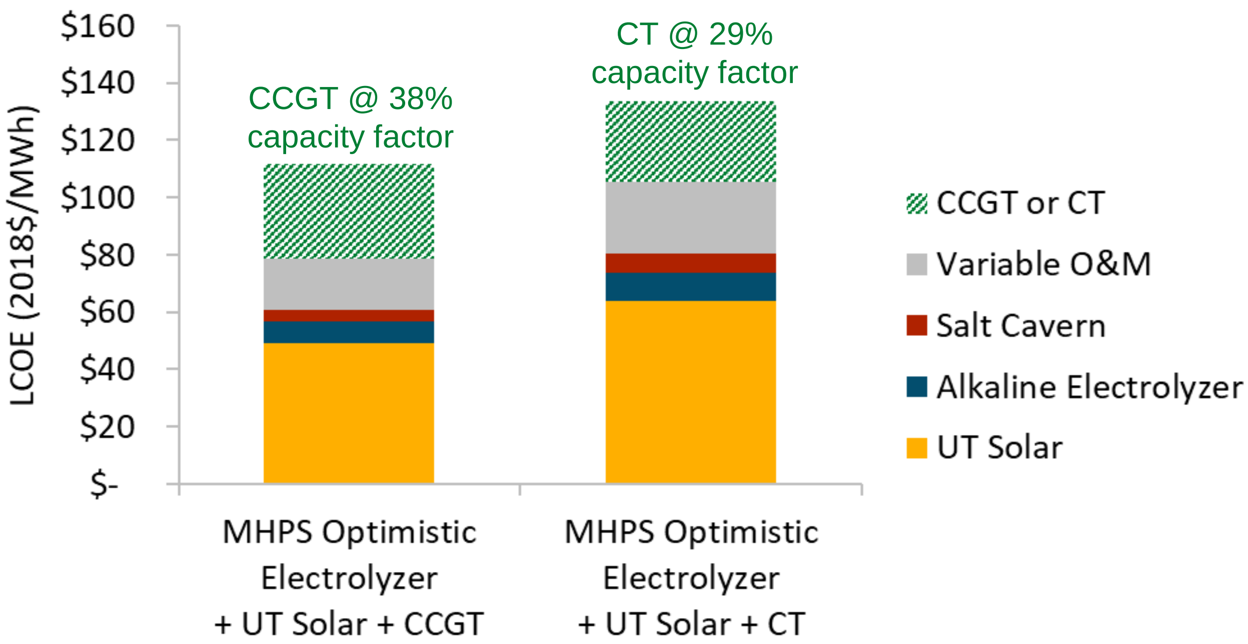
All values for CARB Balanced scenario are for 2045.
***Excluding imports; ~66% including imports.*

H_2 Share of Final Energy Demand by Sector



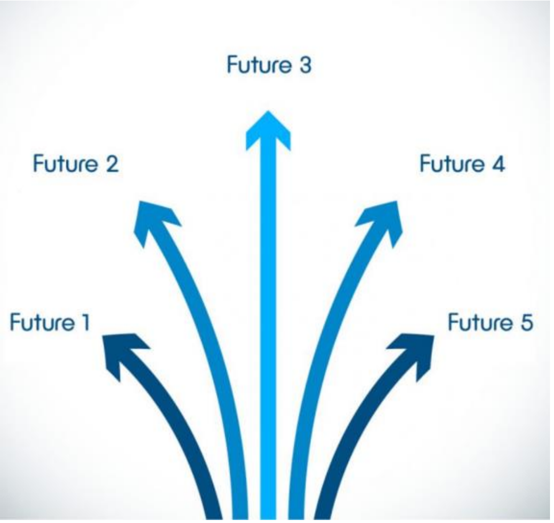
Hydrogen storage LCOE breakdown (2040 costs)

- **Assume solar : CT / CCGT sizing ratio = 2.5 : 1 (MW), based on MHPS input**
  - CT operates at ~30% and CCGT at ~40% capacity factor
- **Electrolyzer and salt cavern account for small portions of LCOE**
- **Solar and gas turbine cost are sensitive to turbine type and capacity factor**
  - Analysis assumes new gas turbines and solar
  - Retrofitting existing CT/ CCGT to burn hydrogen requires local low-cost hydrogen storage or a hydrogen pipeline, but may reduce total LCOE



E3's Scenario-based Approach Reflects Today's Uncertain Markets

+ **California and the broader western electric market currently has a historically high degree of uncertainty**
+ **Fundamental policy and technology factors that are rapidly evolving and interacting in ways that affected market prices**
+ **E3's approach combines**
  - E3's market insight from detailed analysis of long-term fundamentals and cutting-edge research
  - Scenario-based approach that is essential for understanding the impact of these uncertainties
+ **Allows for rapid testing of price sensitivity to a range of futures**
+ **Is bankable and has been relied on by a number of major equity investors and debt providers, especially for hard to value projects**



High-level visualization of E3's market forecast modeling approach

Key Scenario Variables

1. **Scenario-specific load forecasts** (including impact of electrification load)
2. **Scenario-specific policy assumptions**
3. **Regional coordination** (transmission and policy alignment)

4. **Other Major Drivers:**
- Costs of new resources
- Gas prices
- Carbon prices

AURORA Model Outputs

Long-Term Capacity Expansion

Resource Buildout
- Snapshot year resource builds
- Interpolation for interim years

Hourly Production Simulation

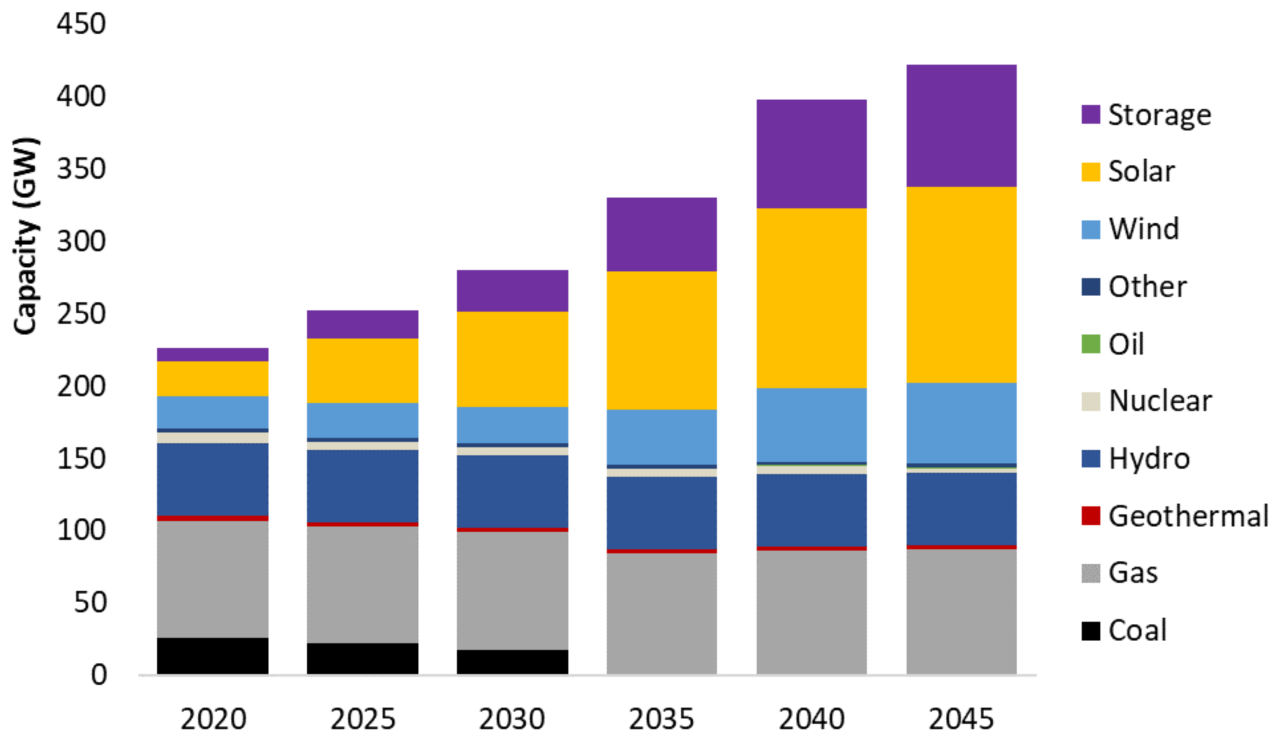
Energy Market Price Forecasts
- Hourly day-ahead energy prices by scenario and by zone
- Dispatch, renewable curtailment, and transmission flows

Derivative Outputs

- Adjusted day-ahead hourly energy prices (reflects REC and scarcity)
- Annual capacity prices
- Ancillary service prices
- Real-time prices

E3's High RPS Case

- Portfolio for the Western U.S. over time in E3's High RPS Aurora Market Price Forecast



Supply side: Assumed RPS/CES policy trajectories across greater WECC grid

+ **RPS/CES policies are defined at the state level for AURORA**
  - How much of state load (or IOU only) must comply?
+ **Future RPS needs are defined based on current and likely future policies**
  - Current: CA SB100, 60% by 2030, 88% by 2050
  - Likely: OR carbon price, AZ 50% RPS by 2030 (recent ballot initiative)
+ **RPS excludes most hydro, a significant carbon-free resource, particularly in PNW**

RPS Policy Scenarios

State	Requirement	Effective RPS Target by 2050
AZ	50% by 2030, 60% by 2040, 70% by 2050	70%
CA	SB 100 *(carbon price at CARB floor)*	88%
CO	30% by 2020; 50% by 2040; 100% for PSCO by 2050	76%
ID	40% by 2040	40%
MT	15% by 2015 for IOU; 40% by 2040 for IOU	33%
NM	50% by 2030; 60% by 2040; 70% by 2050	70%
NV	50% by 2030; 60% by 2040; 70% by 2050	70%
OR	tiered RPS requirement *(carbon price assumed from 2025)*	39%
UT	40% by 2040; 50% by 2050	50%
WA	15% by 2020 *(carbon price assumed from 2025)*	12%
WY	40% by 2040	40%

Demand for renewable hydrogen by "color" depends on highly uncertain factors

- **Carbon-neutral hydrogen can be produced as "green", "blue", or "pink"**
  - Green: Electrolysis using renewable electricity to produce hydrogen from water
  - Pink: Electrolysis using nuclear electricity to produce hydrogen from water
  - Blue: Steam methane reforming (SMR) from natural gas with carbon capture and storage (CCS) (plus direct air capture)

Factors Favoring Green or Pink H_2	Factors Favoring Blue H_2
+ **Cheap or free renewables (green) or cheap advanced nuclear (pink)** + **Higher natural gas prices** + **Slower cost declines in CCS than expected**	+ **Cheap storage capacity for CCS** + **Electrolyzer costs not falling as quickly as some expect** + **Transmission constraints preventing links from lowest cost production areas to load**

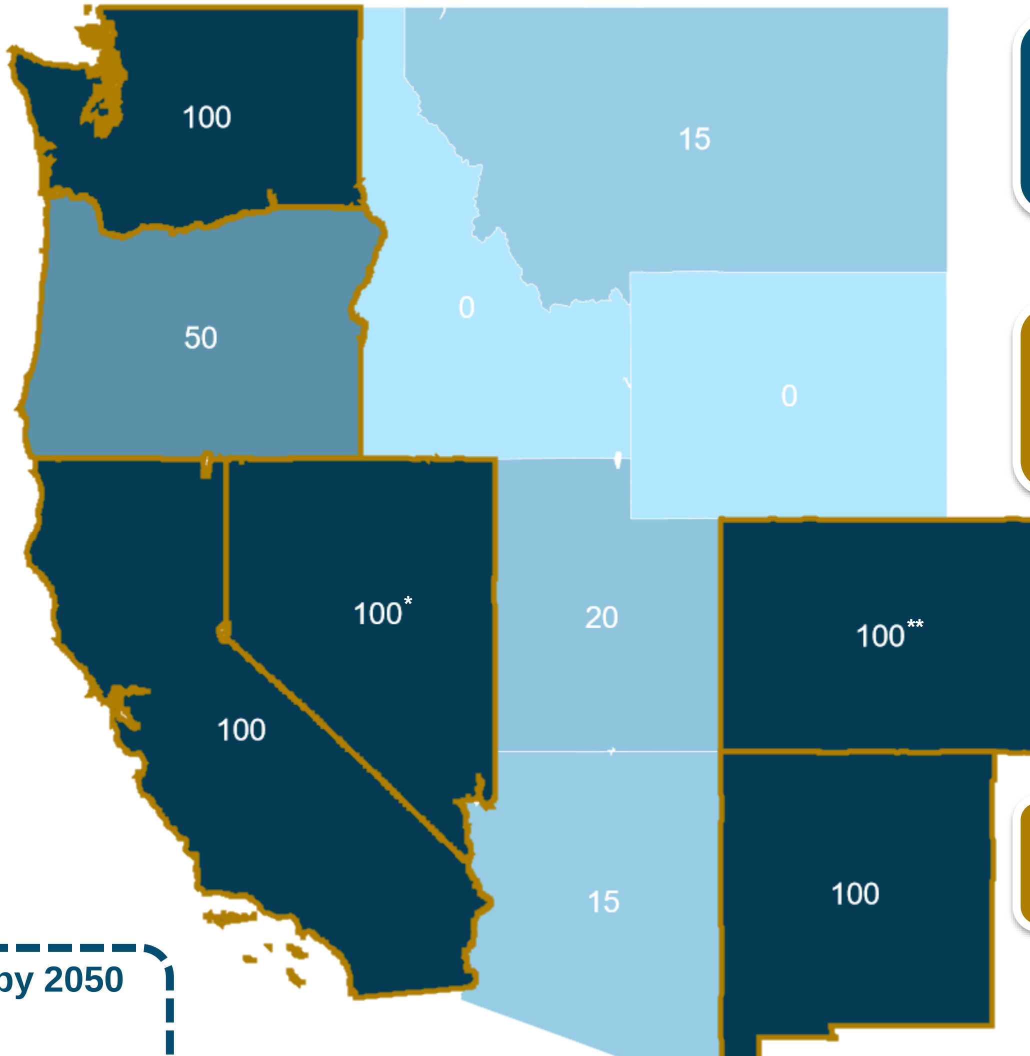
Policymakers across the West are implementing deep decarbonization targets

Washington
- **50% below 1990 by 2050**
- 80% by 2050

Oregon
- **75% below 1990 by 2050**
- 45% by 2035
- 80% by 2050

California
- **40% below 1990 by 2030**
- 80% by 2050
- Carbon neutral by 2045

Nevada
- **45% below 2005 by 2030**
- Near-zero emissions by 2050



CE Target
0 100

Idaho and Wyoming have no clean energy nor economy GHG emission targets

Montana, Arizona, and Utah have no economy GHG emission targets

Colorado
- **90% below 2005 by 2050**

New Mexico
- 45% below 2005 by 2030

Clean energy target (%) by 2050
GHG economy emission
- **Bold = Law**
- Regular = Target

As of December 2019

***Non-binding**
****For utilities serving 0.5M+ customers**