H2@Scale: Hydrogen Integrating Energy Systems

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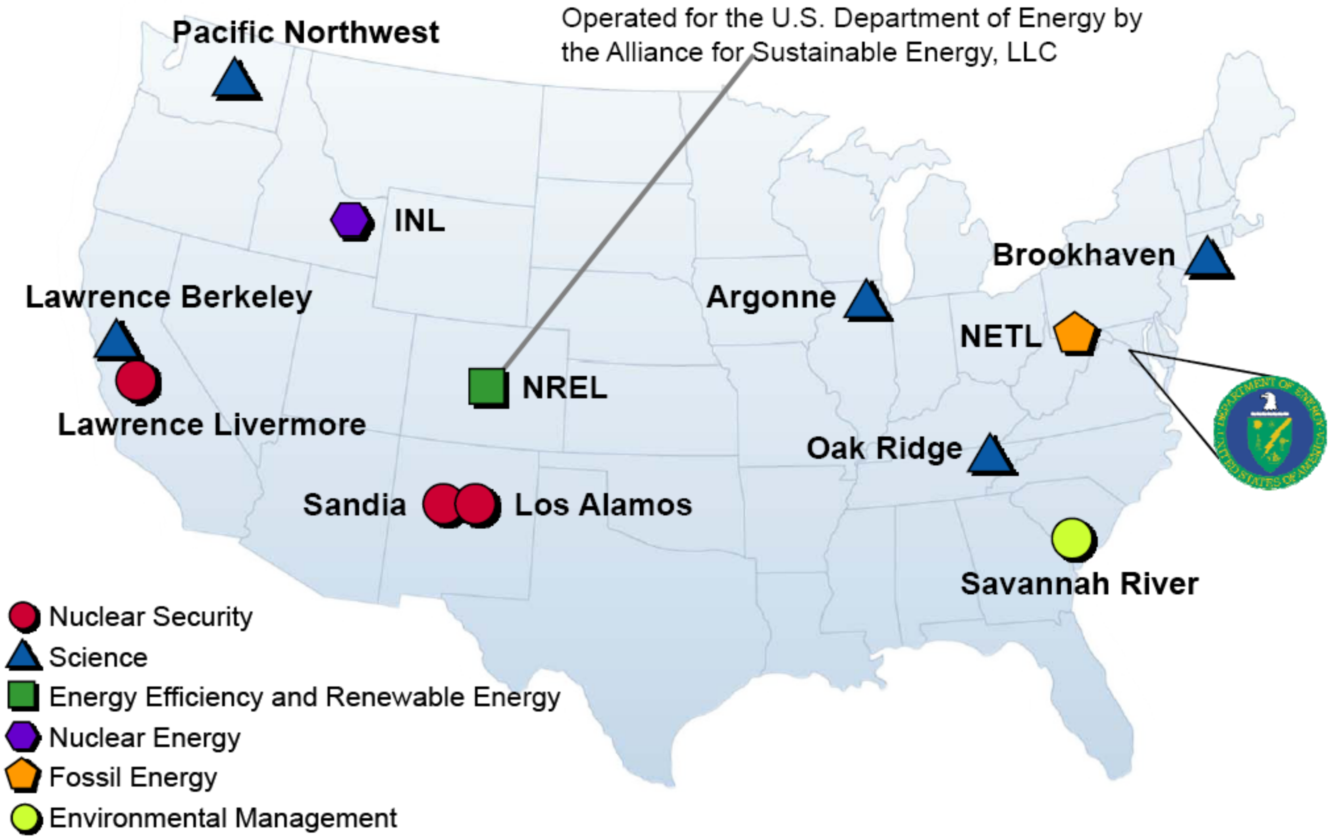
MIT Energy Club
Cambridge, MA
November 13, 2019

Major U.S. National Laboratories



The National Renewable Energy Laboratory

Mission: NREL advances the science and engineering of energy efficiency, sustainable transportation, and renewable power technologies and provides the knowledge to integrate and optimize energy systems.

Example Technology Areas:

- Approximately 2,200 employees, postdoctoral researchers, interns, visiting professionals, and subcontractors
- 327-acre campus in Golden & 305-acre National Wind Technology Center 13 miles north
- 63 R&D 100 awards. More than 1000 scientific and technical materials published annually

www.nrel.gov/about

Partnering with Business for Competitive Advantage

Nearly **820** active partnerships with industry, academia, and government

In **2018** NREL had:

272 new **partnership agreements**

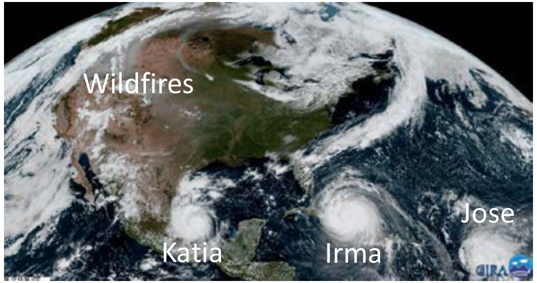
$70.0 million value of new **partnership agreements**

69 unique new **partners**

528 unique active **partners**

Select (Relevant) Megatrends

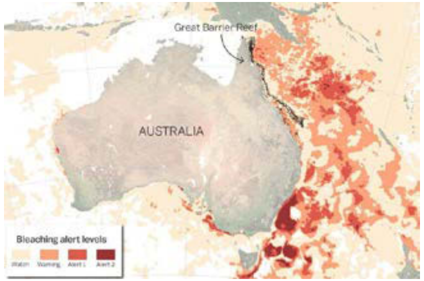
- Increased global focus on emissions, increased policy regulations (market impact)
- Low, cost intermittent renewable electrons
- Increased electrification



When the Planet Looks Like a Climate-Change Ad (9/12/17)
https://www.theatlantic.com/science/archive/2017/09/an-extraordinary-week-in-north-american-weather/539544/

Downtown Denver from NREL's Energy System Integration Facility

The Great Barrier Reef's catastrophic coral bleaching, in one map



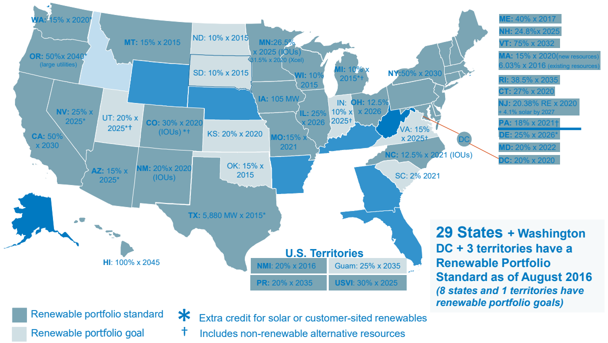
Air Quality – Downtown Denver

27 September 2016 | GENEVA - A new WHO air quality model confirms that 92% of the world's population lives in places where air quality levels exceed WHO limits.

WHO: Air pollution caused one in eight deaths / *March 25, 2014*

http://www.cnn.com/2014/03/25/health/who-air-pollution-deaths/

Changing Energy System – Policy



Renewable Portfolio Standards (RPS)

Senate Bill 100, signed by Gov. Edmund G. Brown, Jr. codifies 60% by 2030 & 100% by 2045 RPS (2018)

http://www.energy.ca.gov/renewables/

Zero Emission Vehicles (ZEV)

2016 ZEV Action Plan toward 1.5 million ZEVs by 2025.

https://www.gov.ca.gov/docs/2016_ZEV_Action_Plan.pdf

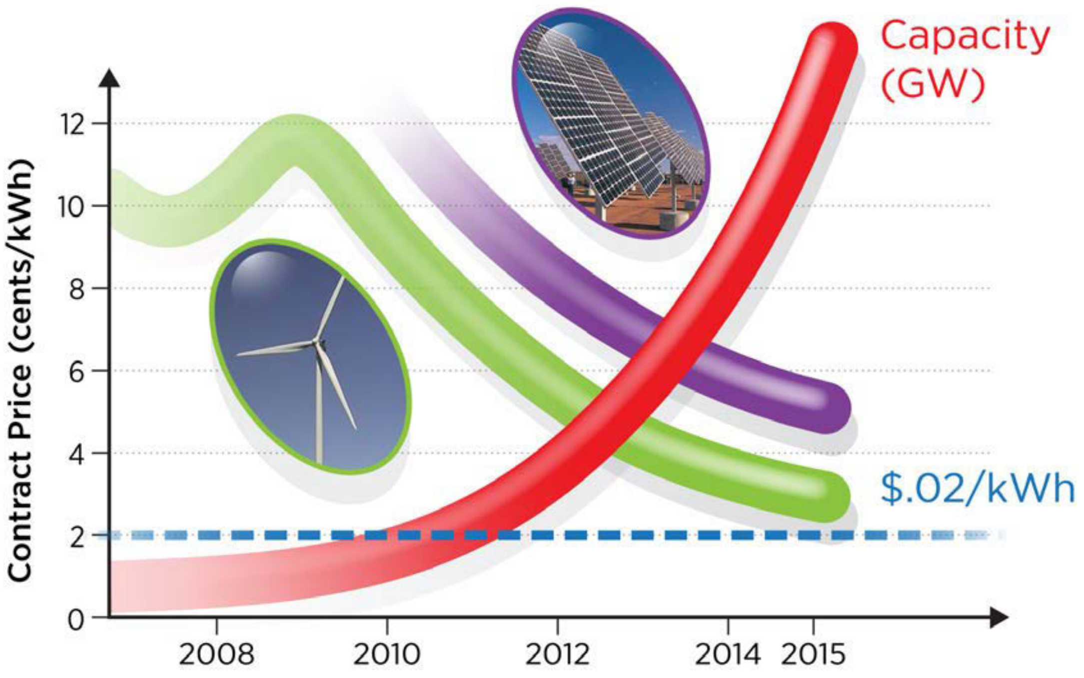
Renewable Gas Standard

SB-687 Renewable gas standard

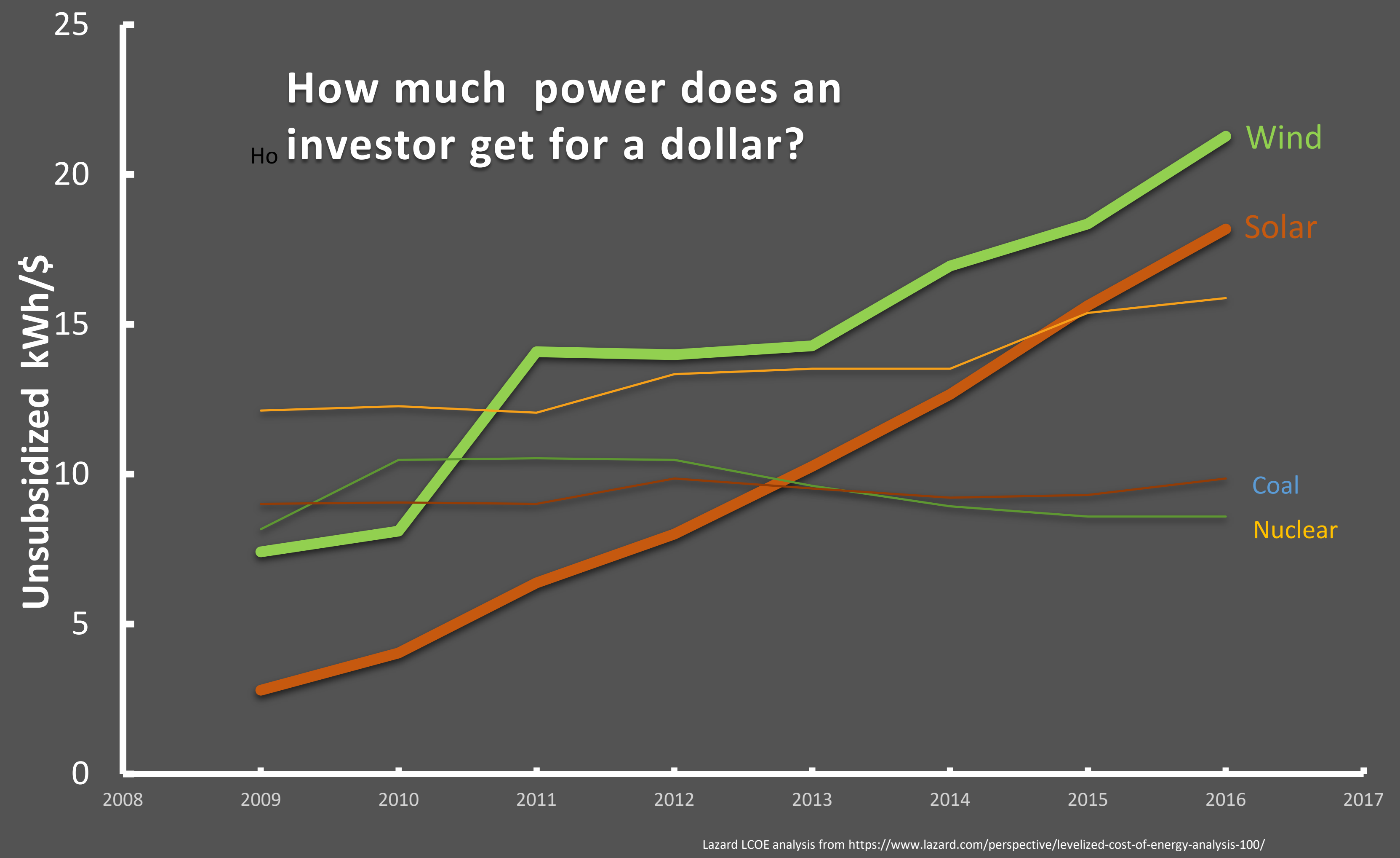
http://leginfo.legislature.ca.gov/faces/billNavClient.xhtml?bill_id=201520160SB687

https://www.c2es.org/us-states-regions/policy-maps/zev-program

Renewable electricity price trends

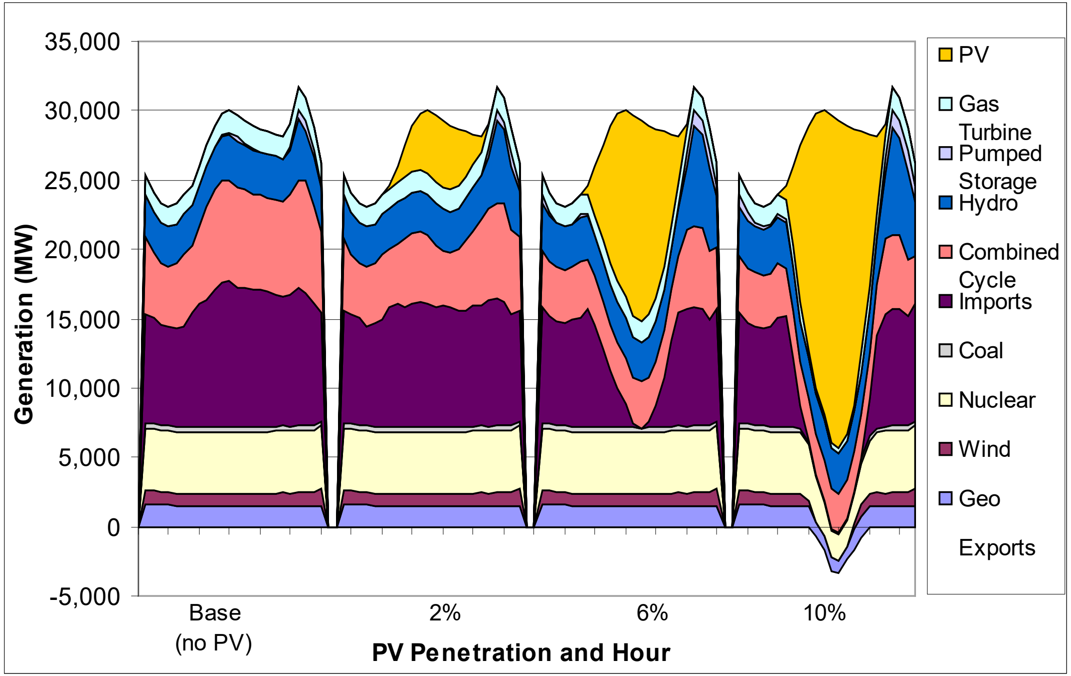


Source: (Arun Majumdar) 1. DOE EERE Sunshot Q1'15 Report, 2. DOE EERE Wind Report, 2015


How much power does an investor get for a dollar?
Ho
Unsubsidized kWh/$
25
20
15
10
5
0
2008
2009
2010
2011
2012
2013
2014
2015
2016
2017
Wind
Solar
Coal
Nuclear
Lazard LCOE analysis from https://www.lazard.com/perspective/levelized-cost-of-energy-analysis-100/

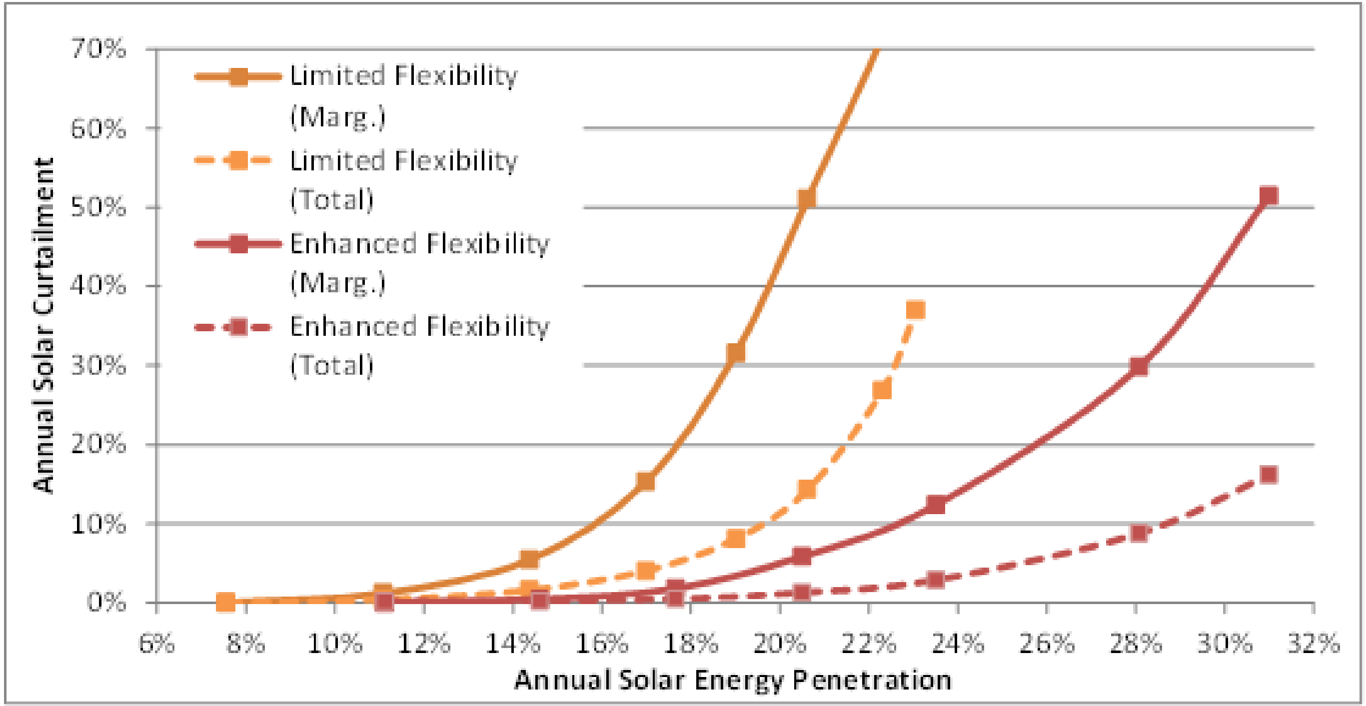
Variable Renewable Electricity Challenges

Denholm et al. 2008



Limitations of Matching Load/Generation

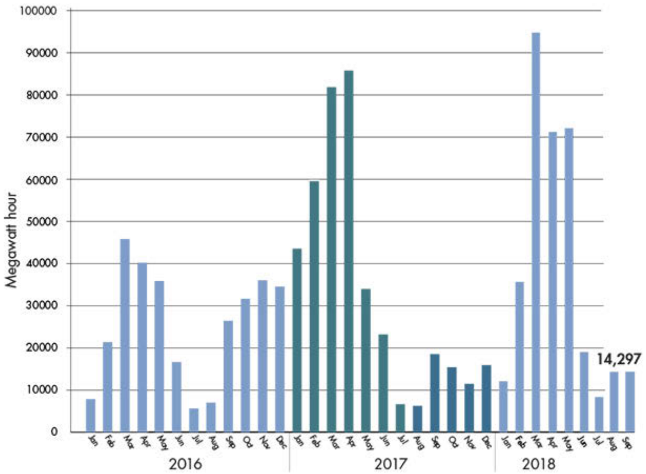
Denholm, P.; M. O'Connell; G. Brinkman; J. Jorgenson (2015) Overgeneration from Solar Energy in California: A Field Guide to the Duck Chart. NREL/TP-6A20-65023

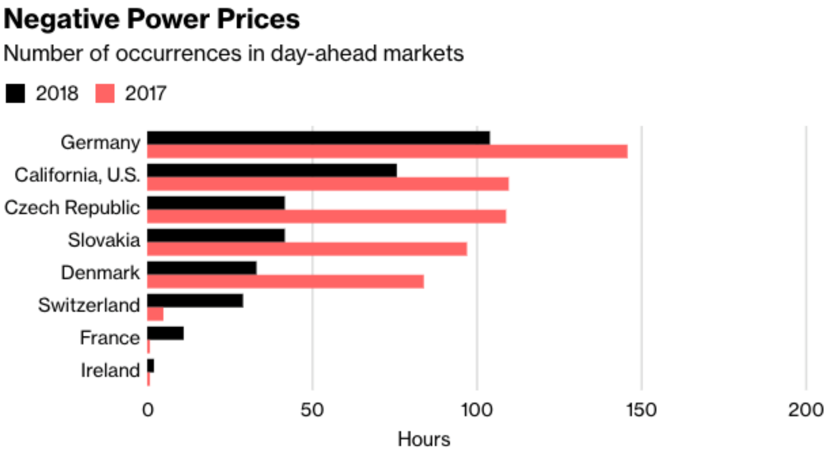


Curtailment will lead to an abundance of low value electrons, and we need solutions that will service our multi-sector demands

Curtailment and Electricity Prices

Curtailment is increasing

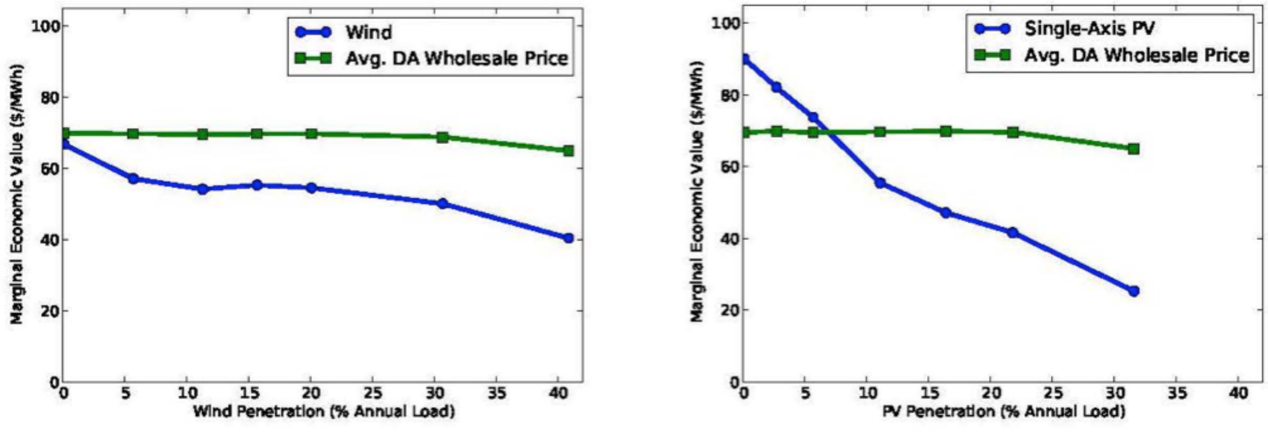




Lower average electricity prices and hours with negative prices

Sources: https://www.ucsusa.org/sites/default/files/attach/2015/08/Achieving-50-Percent-Renewable-Electricity-In-California.pdf (August 2015); Jesper Slarn "Power Worth Less Than Zero Spreads as Green Energy Floods the Grid" https://www.bloomberg.com/news/articles/2018-08-06/negative-prices-in-power-market-as-wind-solar-cut-electricity (August 5, 2018)

Impacts of Curtailment Renewable Investment



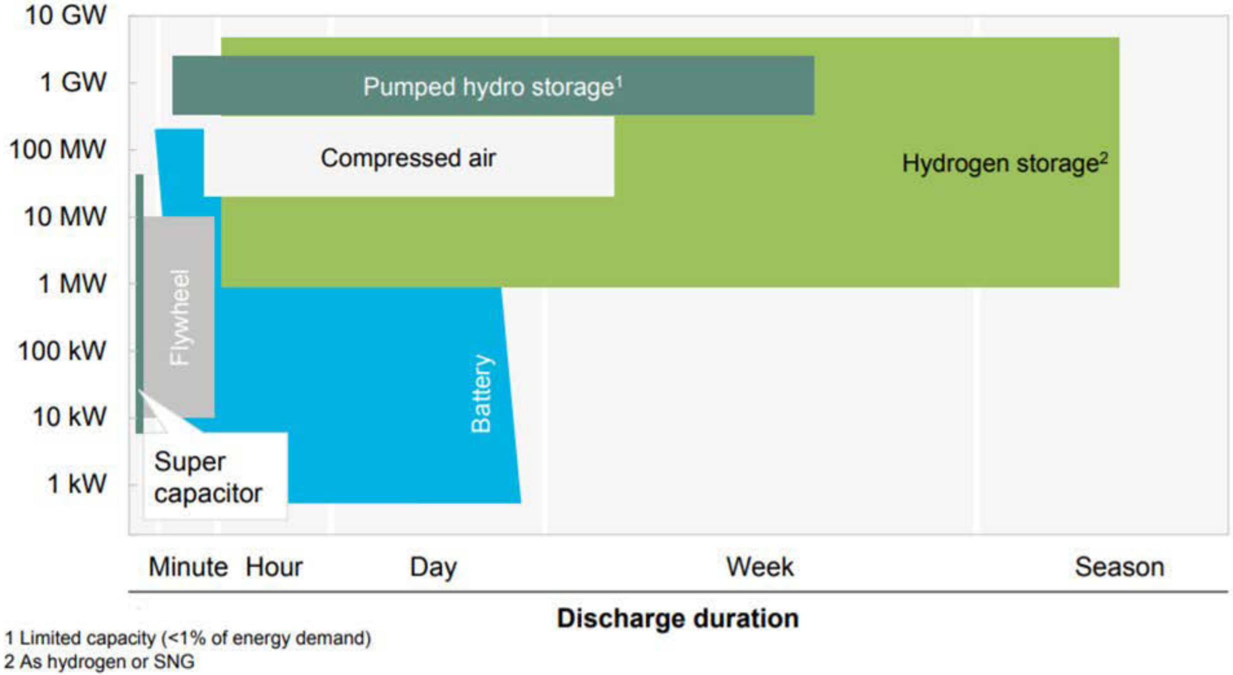
(a) Wind (b) PV

- Reduced revenue would likely limit penetration of VRE generation outside of policy factors (RPS)
- If a purchaser could accept a low utilization factor, they could get low-price electricity and extend the VRE penetration limit

Source: A. Mills & R. Wiser (2012) “Changes in the Economic Value of Variable Generation at High Penetration Levels: A Pilot Case Study of California” Technical Report: LBNL-5445E

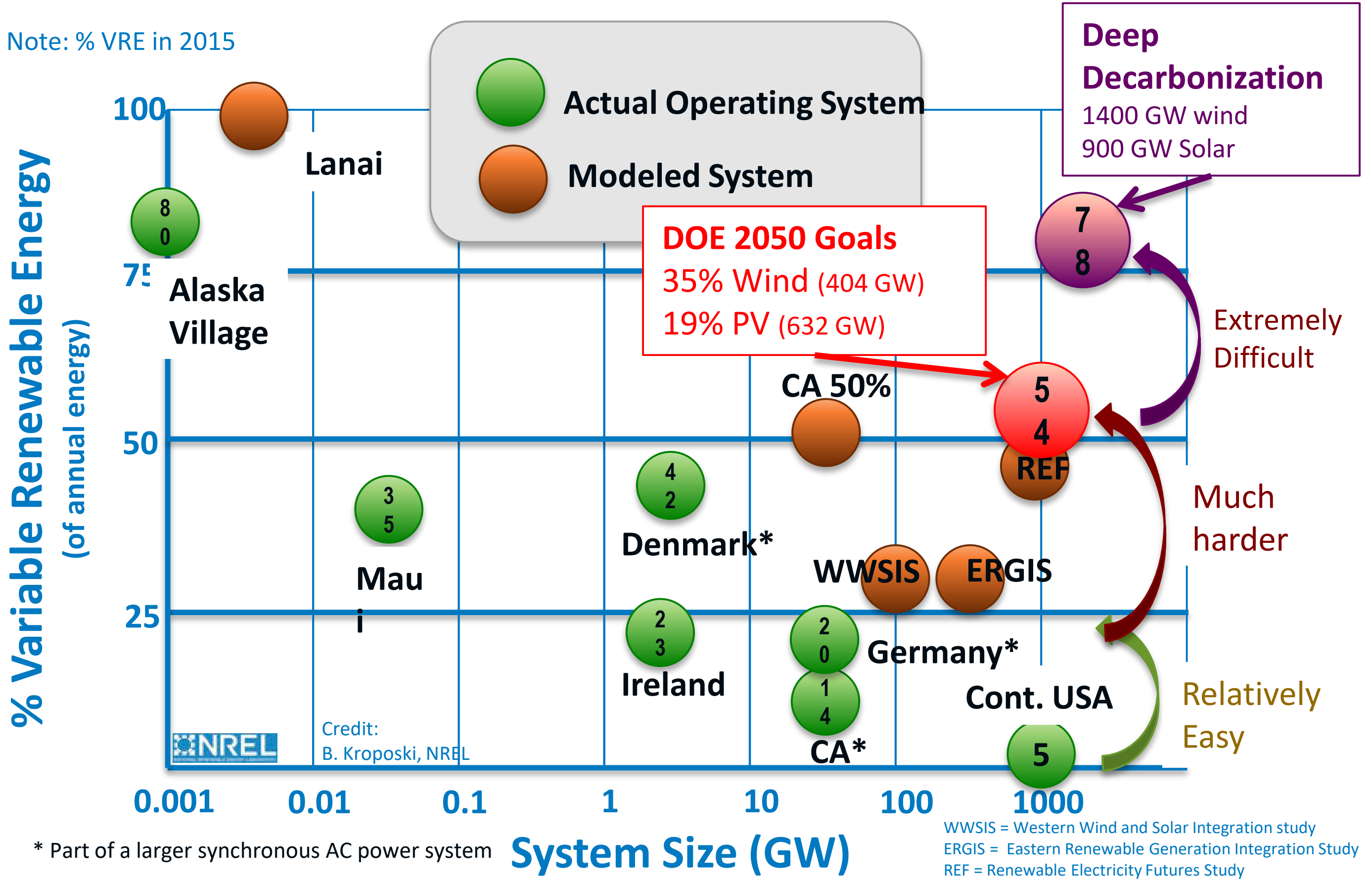
Options for Storing Electrical Energy

Long-term (e.g., seasonal) storage is challenging



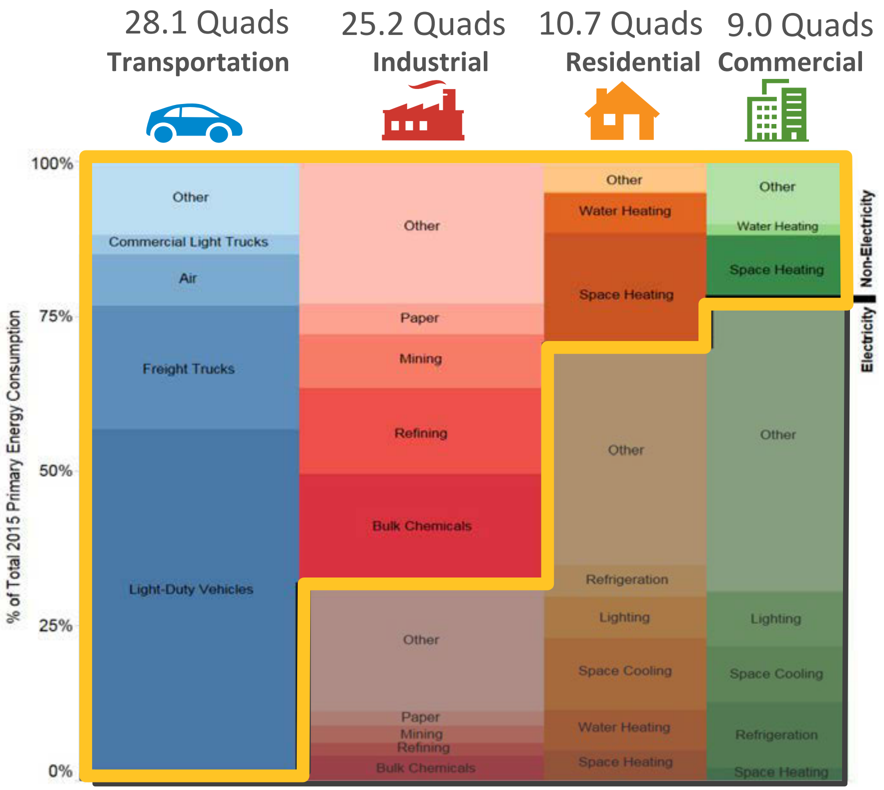
Source: Hydrogen Council. 2017. "Hydrogen Scaling Up: A Sustainable Pathways for the Global Energy Transision." http://hydrogencouncil.com/wp-content/uploads/2017/11/Hydrogen-Scaling-up_Hydrogen-Council_2017.compressed.pdf

Challenges Reaching High Renewable Electricity Penetrations



Electricity is Not the Only Energy Challenge

- Electrification is increasing in utilization sectors
- But they have limited electricity options
- Reducing emissions will need a combination of efficiency and reduced carbon sources



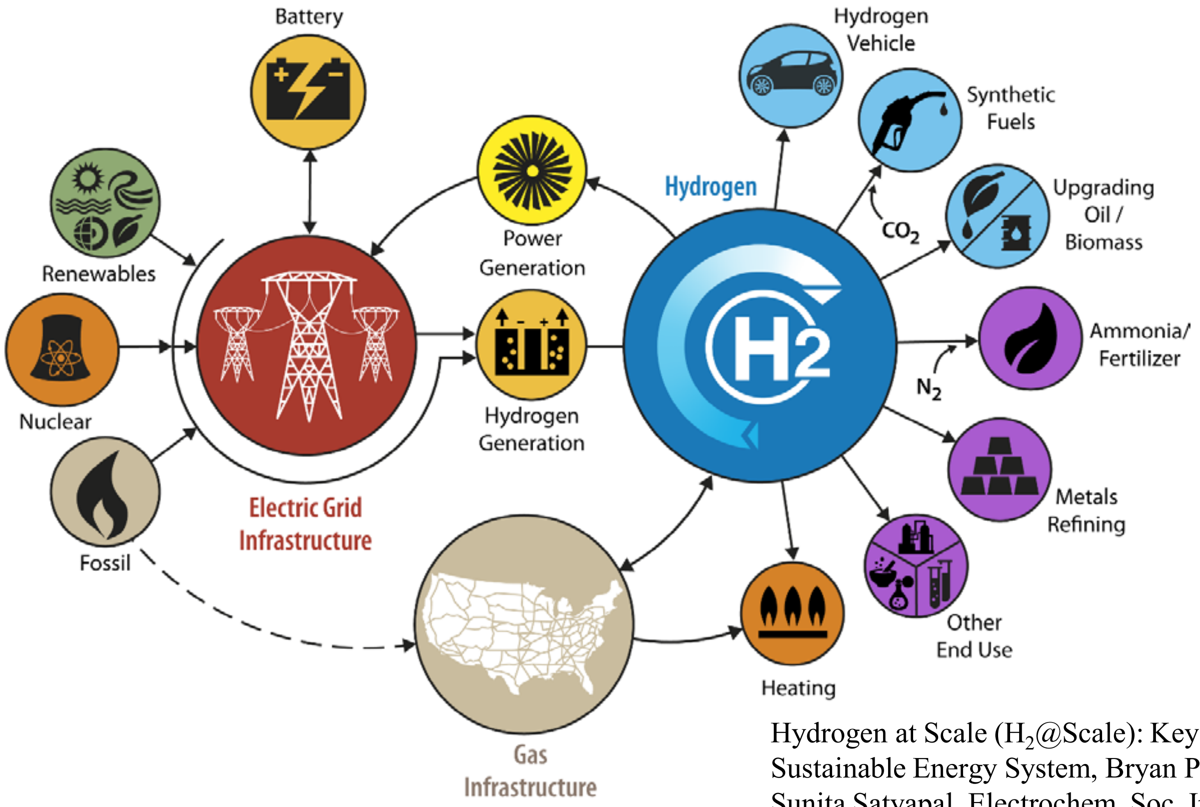
Source: https://www.nrel.gov/analysis/electrification-futures.html

"If you can't solve a problem, enlarge it"

President Dwight D. Eisenhower

Source: https://www.whitehouse.gov/sites/whitehouse.gov/files/images/first-family/34_dwight_d_eisenhower%5B1%5D.jpg

H2@Scale Concept



*Illustrative example, not comprehensive

Hydrogen at Scale (H_2@Scale): Key to a Clean, Economic, and Sustainable Energy System, Bryan Pivovar, Neha Rustagi, Sunita Satyapal, Electrochem. Soc. Interface Spring 2018 27(1): 47-52; doi:10.1149/2.F04181if

H_2 is different and changing fast

H_2 Council*

– Launched in January 2017 its members include leading companies with over $10 billion in investments along the hydrogen value chain, including transportation, industry, and energy exploration, production, and distribution.

> ***Potential Impacts from Hydrogen Council Roadmap Study. By 2050:***
> - *$2.5 trillion in global revenues*
> - *30 million jobs*
> - *400 million cars, 15-20 million trucks*
> - *18% of total global energy demand*

AIR LIQUIDE Creative Oxygen · ALSTOM · AngloAmerican · BMW GROUP · DAIMLER · ENGIE by people for people · HONDA · HYUNDAI · Kawasaki · Shell · THE LINDE GROUP · TOTAL · TOYOTA

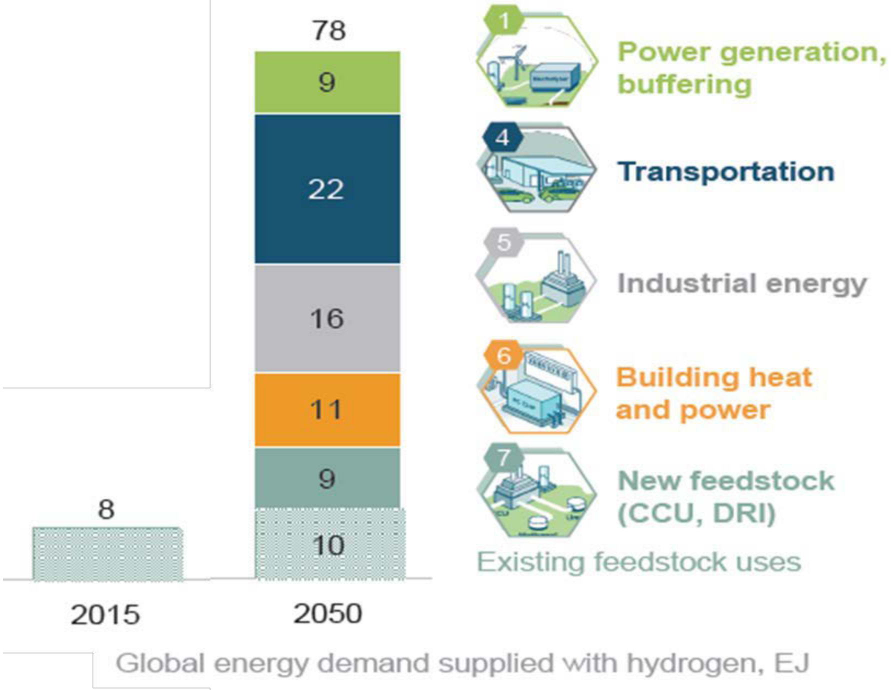
13 members (Jan 2017).

32 steering members and 20 supporting members (Nov 2018).

*Steering members shown, additional supporting members
www.hydrogencouncil.com

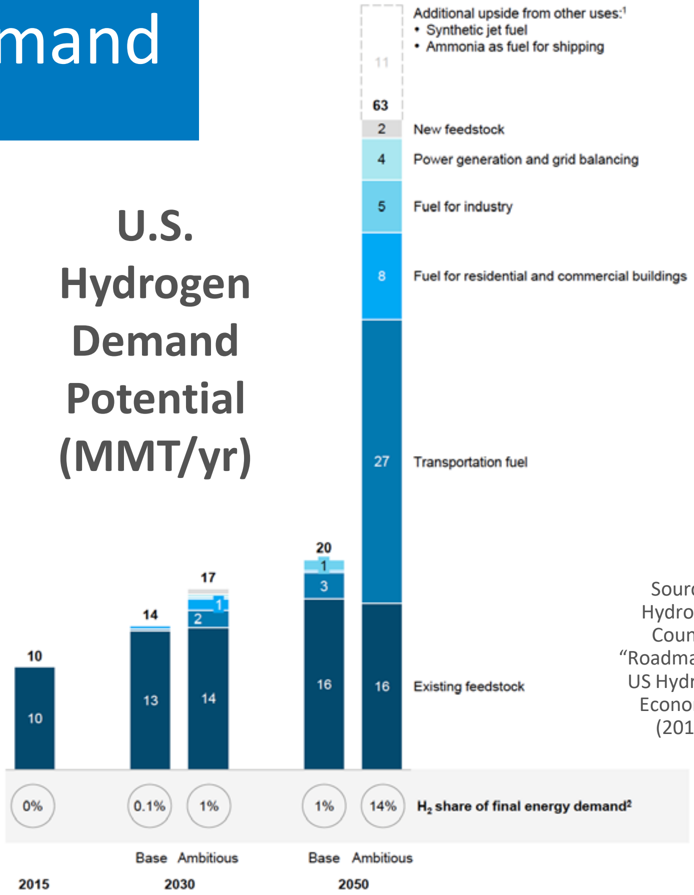
Potential Growth in Hydrogen Demand

Global Hydrogen Demand Potential (EJ)



Source: Hydrogen Council "Hydrogen Scaling Up"

U.S. Hydrogen Demand Potential (MMT/yr)



Source: Hydrogen Council "Roadmap to a US Hydrogen Economy" (2019)

H_2 Council: Opportunity for 6-10-fold increase by 2050

Demand Potential

Demand potential of hydrogen market by 2050 is >9X.

Other applications are possible based on technology and policy growth as well as smaller applications

Application	Demand Potential (MMT/yr)	2015 Market for On-Purpose H2 (MMT/yr)
Refineries and the chemical processing industry (CPI) [a]	8	6
Metals	12	0
Ammonia	4	3
Biofuels	4	0
Synthetic fuels and chemicals	14	1
Natural gas supplementation	10	0
Seasonal energy storage for the electricity grid	15	0
Industry and Storage Subtotal	**67**	**10**
Light-duty fuel cell electric vehicles (FCEVs)	21	0
Medium- & Heavy-Duty FCEVs	11	0
Transportation Fuel Subtotal	**32**	**0**
Total	**99**	**10**

Preliminary Results

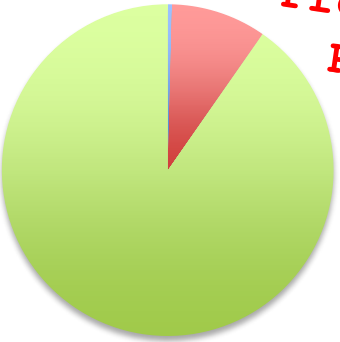
Definition: The demand potential is the estimated market size constrained by the services for which society currently uses energy, real-world geography, system performance, and by optimistic market shares but not by economic calculations.

Technical Potential Supply from Renewable Resources

	EIA 2015 current consumption (quads/yr)	Required to meet demand of 99 MMT / yr (quads/yr)	Technical Potential (quads/yr)
Solid Biomass	4.7	24	19
Wind Electrolysis	0.68	16	170
Solar Electrolysis	0.17	16	1,000

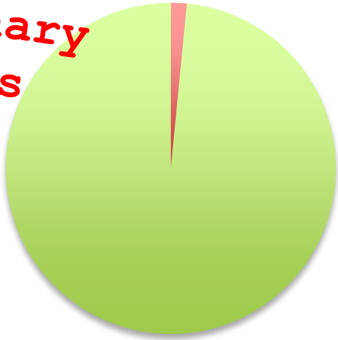
Total demand including hydrogen is satisfied by ≈10% of wind, 2% of solar, and ≈150% of biomass technical potential

Wind Technical Potential



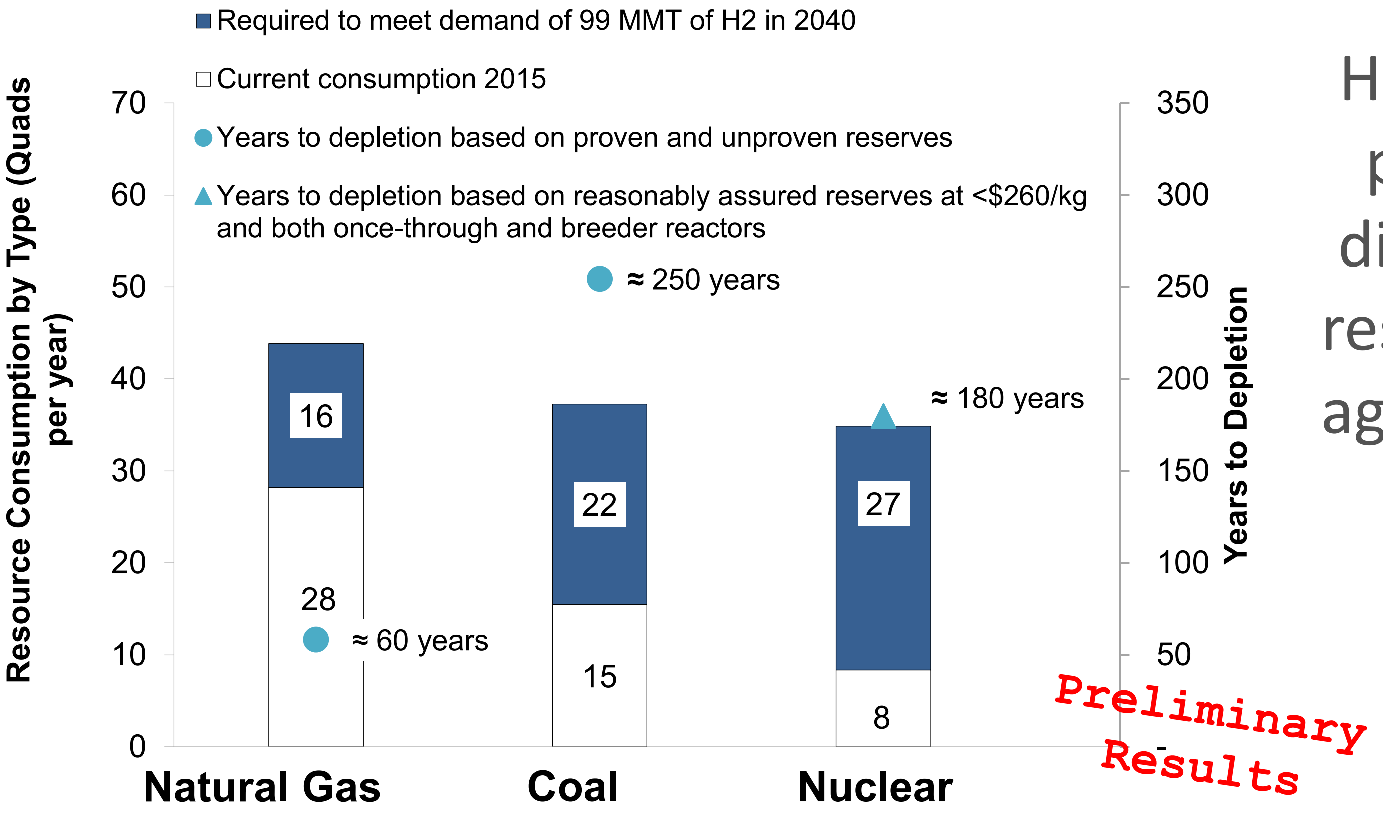
Preliminary Results

Solar Technical Potential



Current consumption 2015
Required to meet demand of 99 MMT of H2
Residual Technical Potential

Technical Potential of Fossil and Nuclear Resources



Hydrogen can be produced from diverse domestic resources to meet aggressive growth in demand

Electricity Prices Vary Across the Year

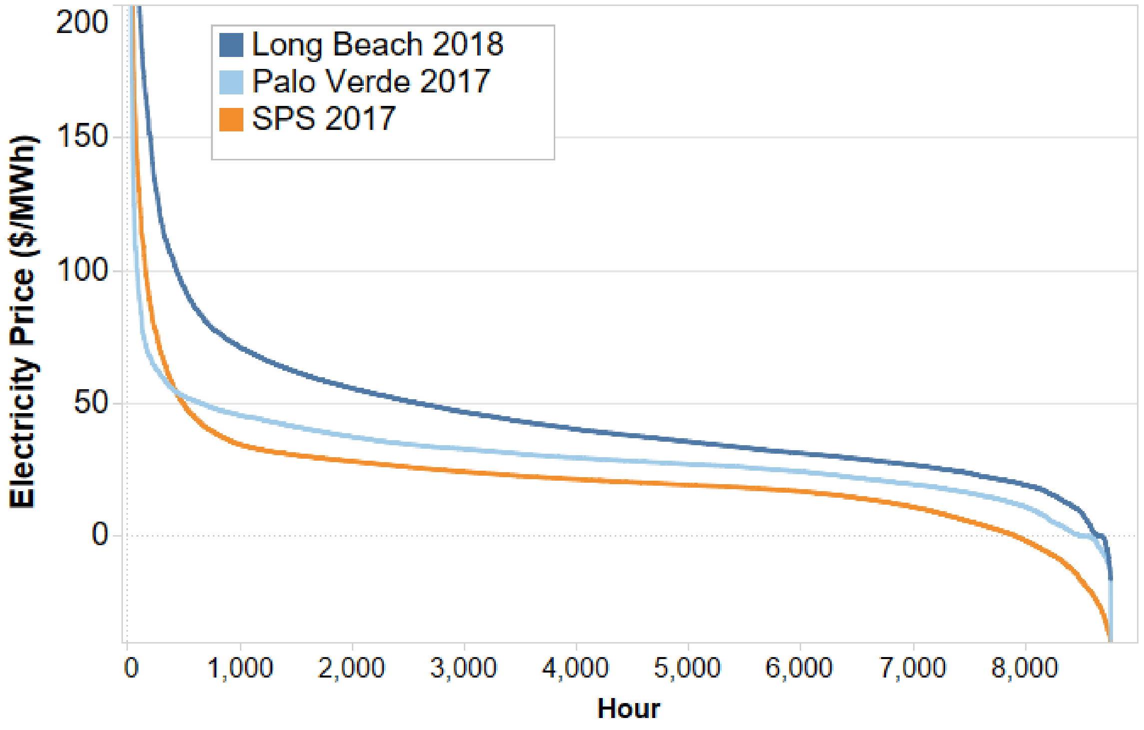
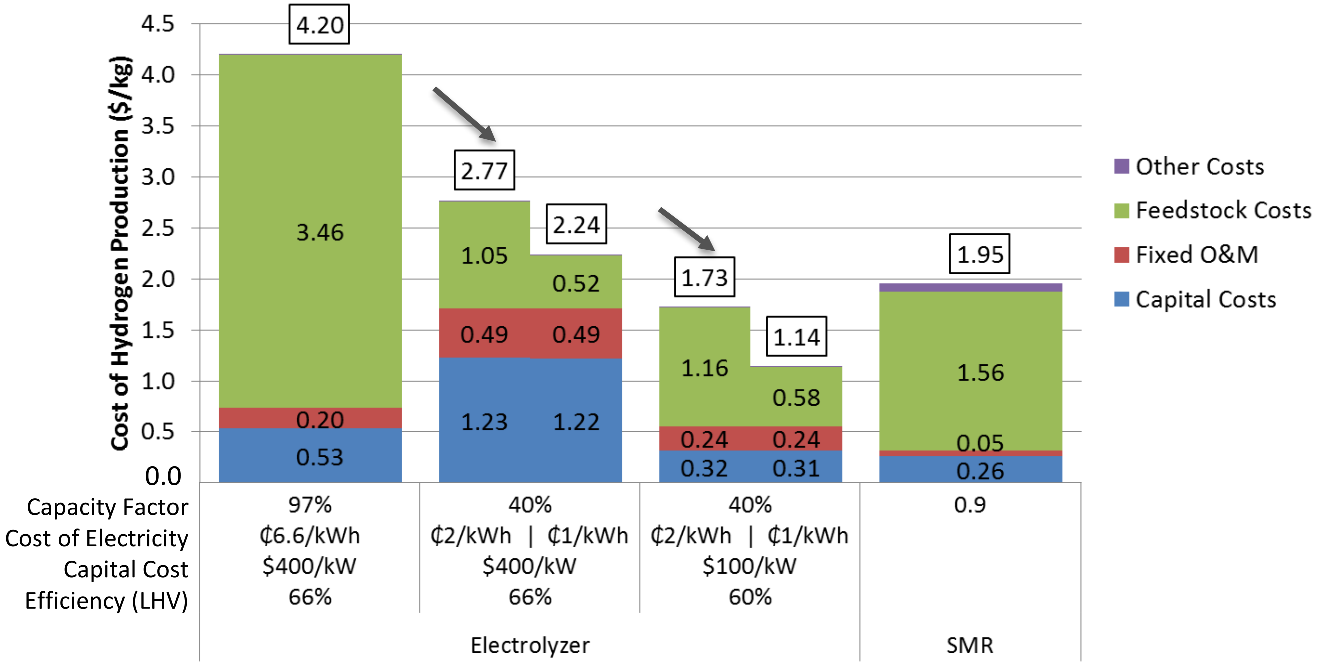


Figure created using data from publicly available CA-ISO and SPP datasets

- Hours with energy at very low and very high prices are increasing
- Other revenue streams (e.g., capacity, services) are becoming more critical
- Wind and solar power purchase agreements (PPAs) are key opportunities

Potential Opportunity: Low Temperature Electrolysis

Potential Levelized Costs of H_2 Production

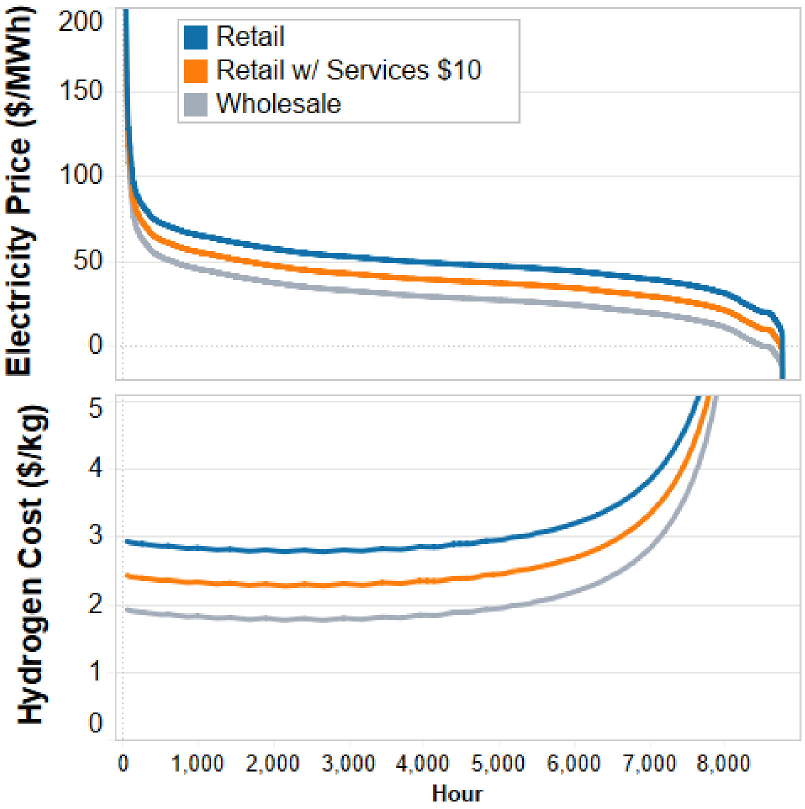


Electrolytic H_2 has the potential to be cost competitive.

Availability of low-cost electricity can help enable low-cost H_2 production, even at low capacity factors.

Source: Bryan Pivovar & Josh Eichman

Opportunity for Electrolytic Hydrogen Generation



Palo Verde 2017

- Electrolytic hydrogen could be cost-competitive if flexible, low-temperature electrolyzers can be purchased at $400/kW and markets are available

$400/kW electrolyzer purchase cost. Operating during lowest cost hours of the year

A Dispatchable Load Could Utilize Low-Cost, Dispatch-Constrained Electricity (LDE)

A controllable, dispatchable load could remove the cap on penetration of variable renewable generation

We developed a method to estimate LDE availability providing a flexible load will pay for it.

Set willingness to pay for LDE

↓

Run ReEDS to estimate optimal generator fleet

↓

Transfer fleet results to PLEXOS

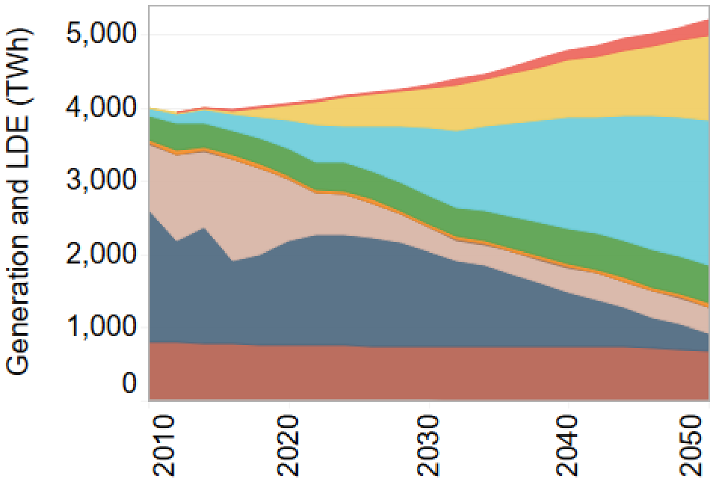
↓

Run PLEXOS to estimate quantity and availability of LDE

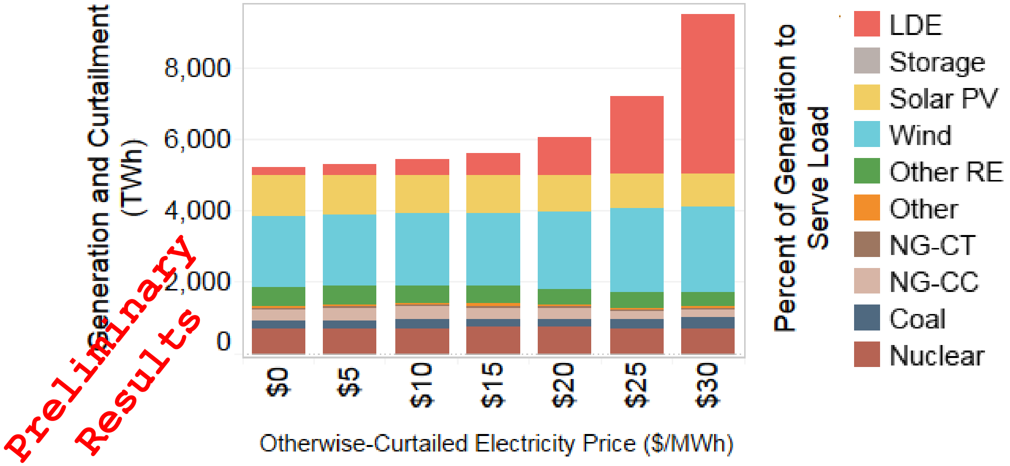
LDE Generation

Used ReEDS to estimate generator fleet and generation mix at multiple LDE values

Buildout with $0/MWh LDE

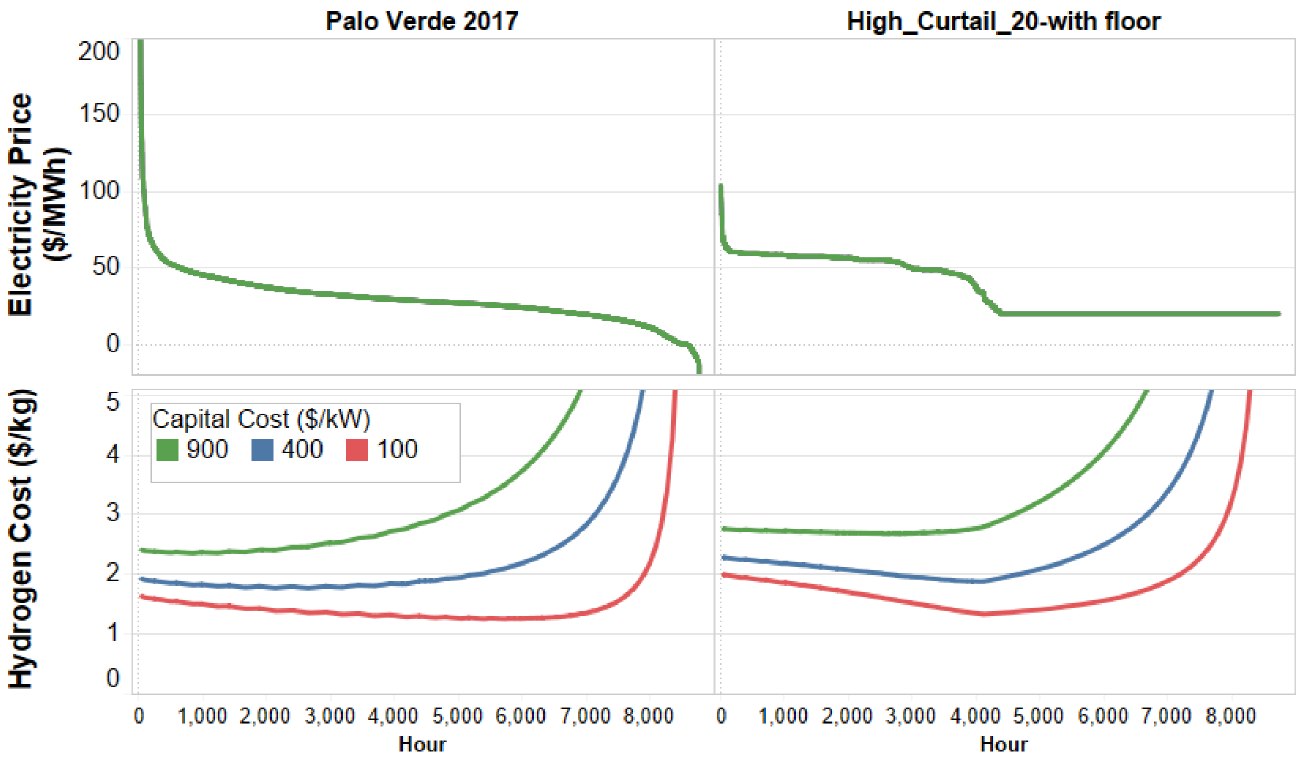


2050 Results at Various LDE Values



High Curtailment Scenario

Future Opportunities for LDE Utilization at Palo Verde

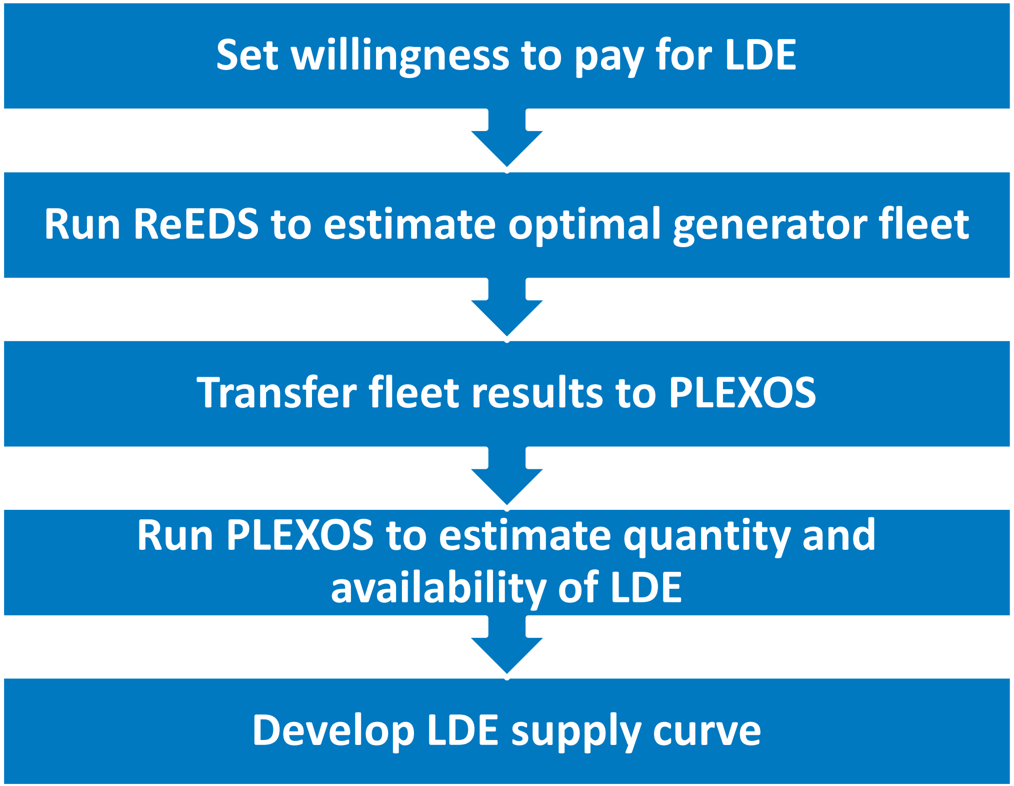


Under parameters that lead to high variable renewable generation and with a $20/MWh price floor,

- Additional LDE is available
- Electrolytic hydrogen can be cost competitive at Palo Verde

A Dispatchable Load Could Utilize Low-Cost, Dispatch-Constrained Electricity (LDE)

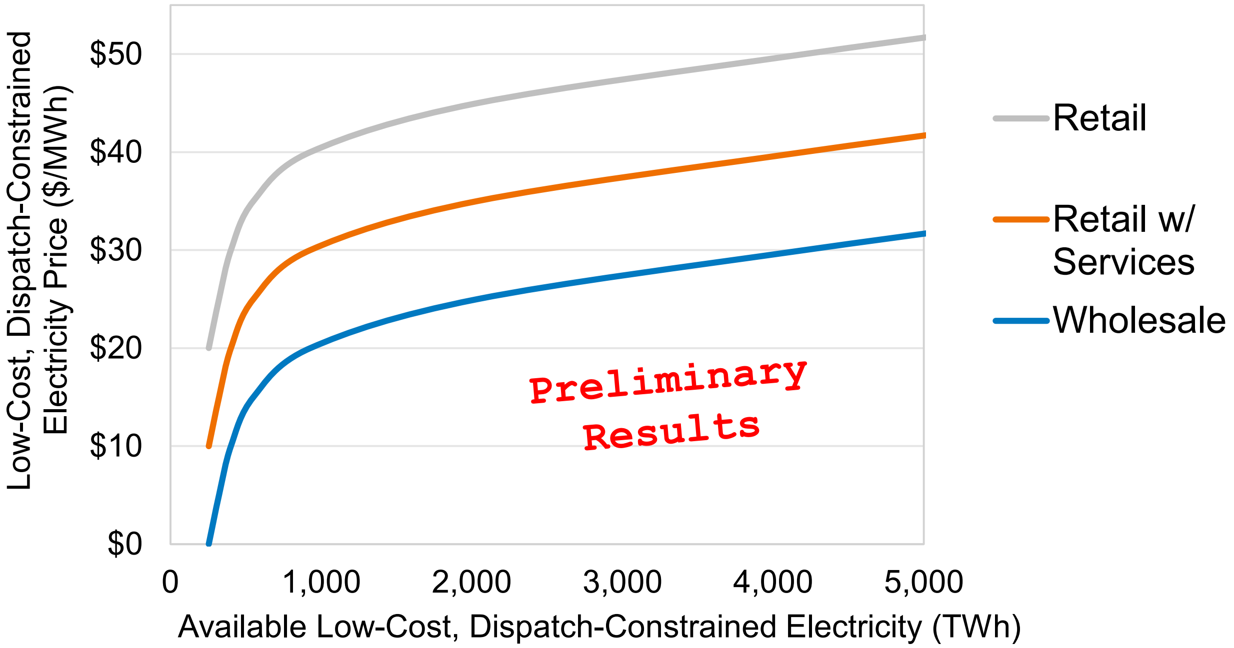
A controllable, dispatchable load could remove the cap on penetration of variable renewable generation



We developed a method to estimate LDE availability providing a flexible load will pay for it.

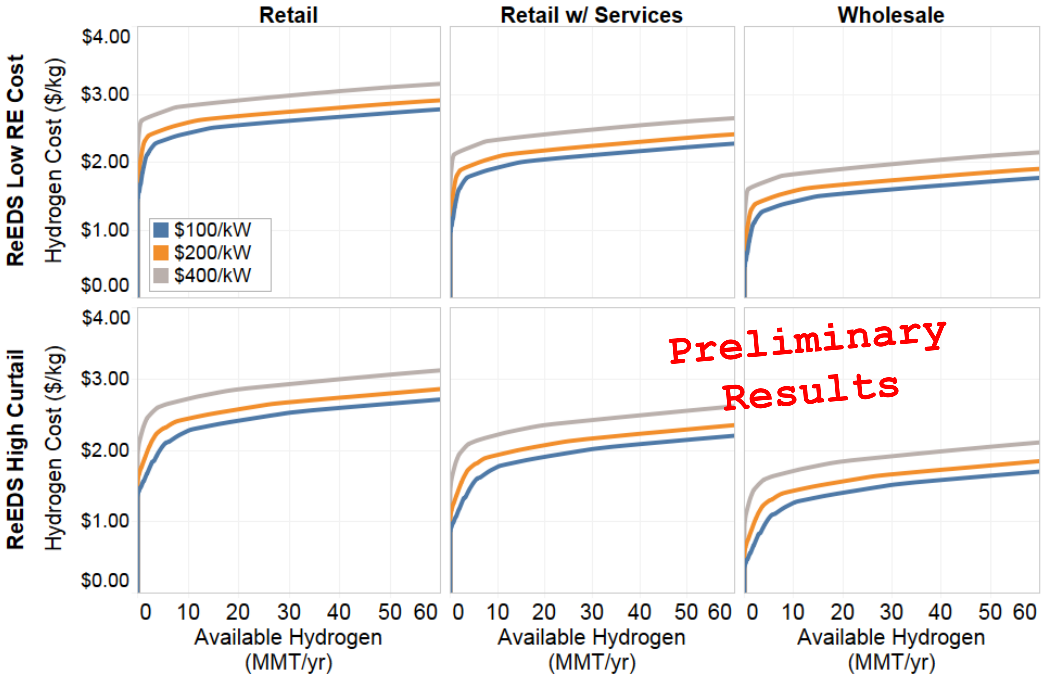
LDE Supply Curves

Used PLEXOS Unit Commitment Model to create supply / availability curves for LDE



Used LDE Supply Curves in H2@Scale Economic Potential Analysis

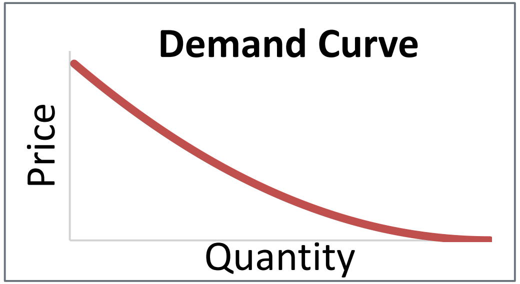
Developed supply curves for LTE-generated hydrogen based on each price / availability factor combination

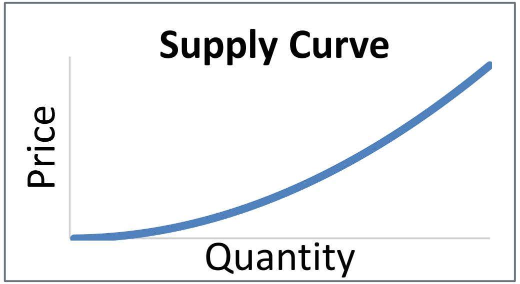


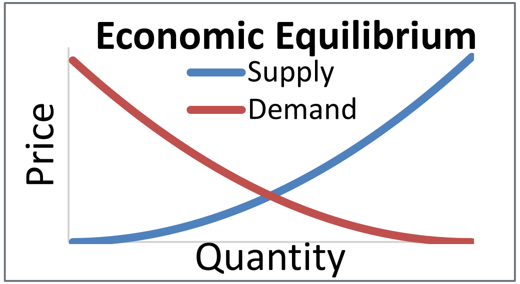
Low Temperature Electrolysis of Low-Cost, Dispatch-Constrained Electricity:

- **Calculated hydrogen levelized costs** using H2A Future Central Hydrogen Production from PEM Electrolysis model at each price / availability factor combination
- Added **$20/MWh for transaction fees** for "Retail" prices and **$10/MWh for "Retail w/ Services"**
- Assume storage and delivery costs ~$0.40/kg$_{H2}$ (cost for pipeline transport of 200,000 MT/yr 250 miles with geologic storage)

Economic Potential Methodology: Market Equilibrium







Demand Curve: how much are consumers willing and able to pay for a good?

Supply Curve: threshold prices showing how much are producers willing and able to produce at each?

Economic Equilibrium: Quantity where demand price is equal to the supply price.

- No excess supply or demand.
- Market pushes price and quantity to equilibrium.

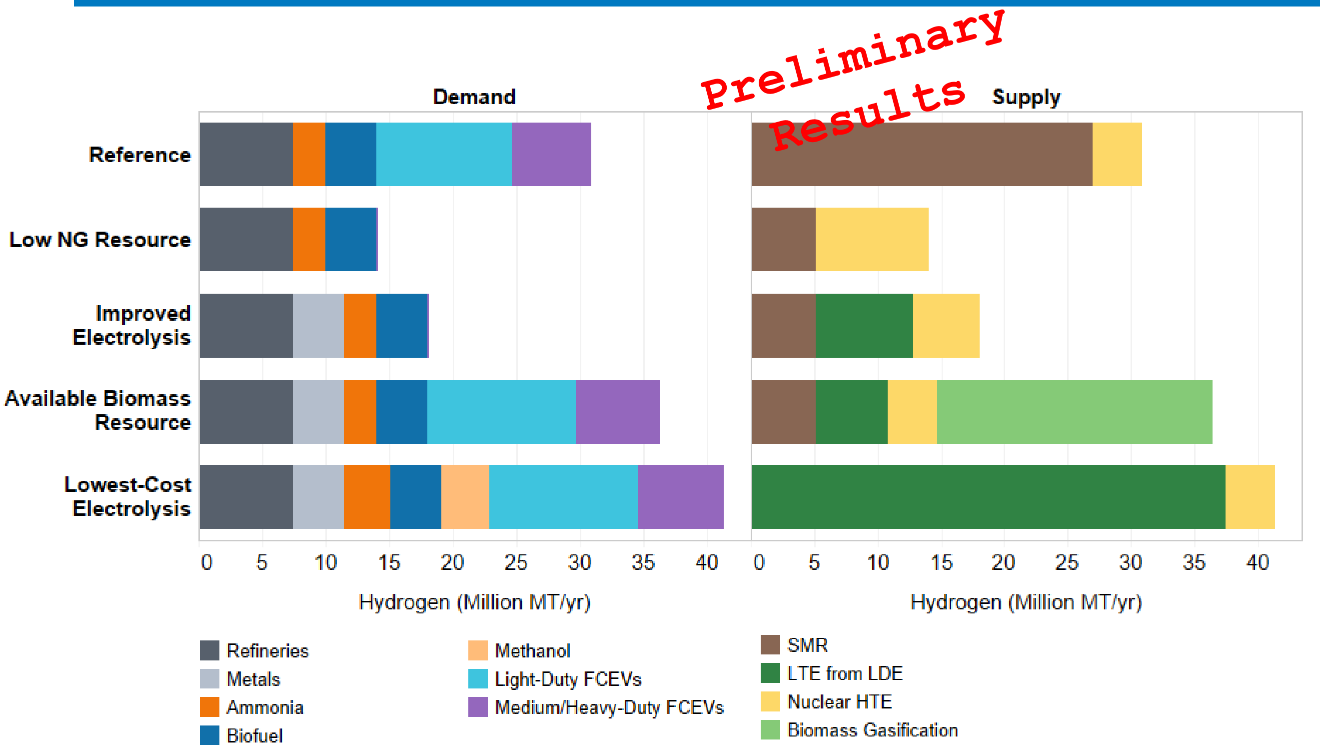
Methodology described in Schwartz, Robert A. *Micro Markets A Market Structure Approach to Microeconomic Analysis*. Wiley Finance. Chichester: Wiley, 2010.

Economic Potential: Five National Scenarios

Scenario Name	Reference	Low NG Resource	Improved Electrolysis	Available Biomass Resource	Lowest-Cost Electrolysis
Natural gas price assumption	Reference	Higher			
Low-Temperature Electrolysis (LTE) capital costs Low-cost, Dispatch-constrained Electricity purchase assumption	Current Trajectory		Improvements		Aggressive Assumptions
Biomass	**Not available**			Available	Not Available
Metals demand	**Competitive Market**		**Premium Available**		

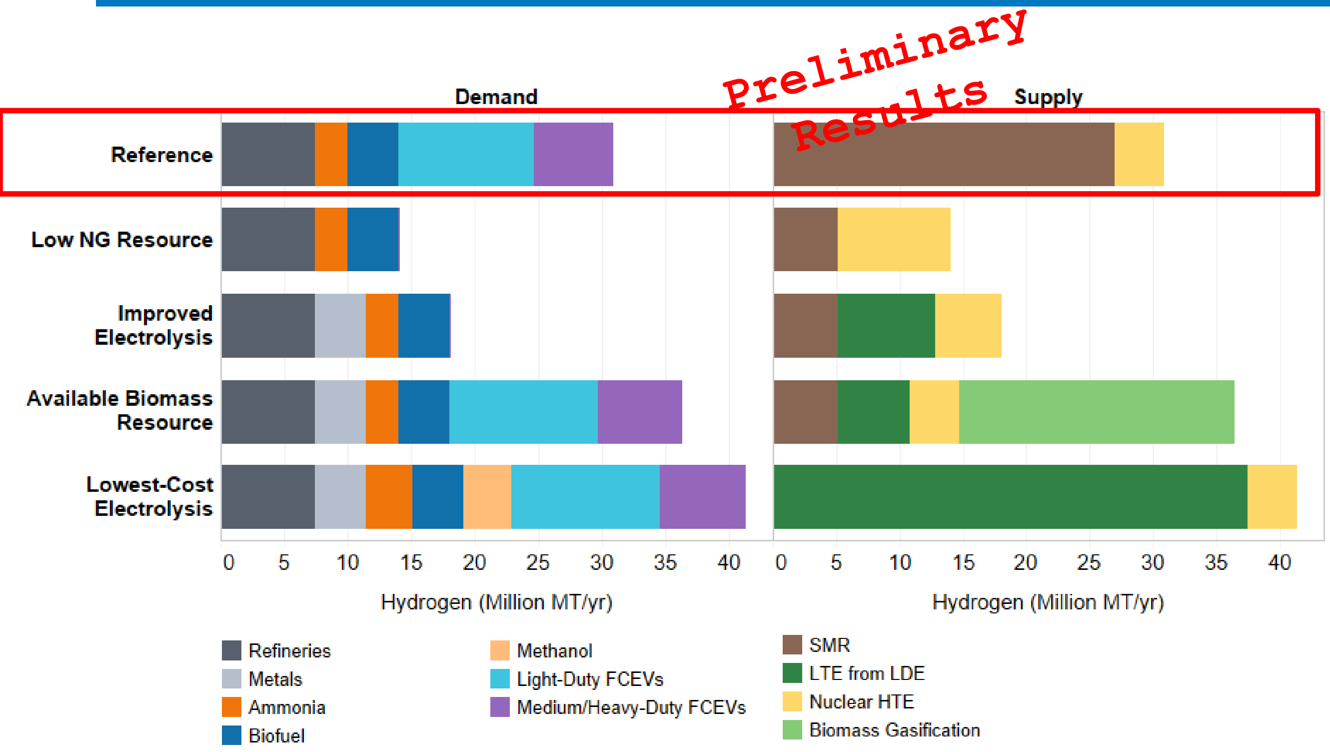
Key differences in scenarios: 1) natural gas price assumption, 2) electrolyzer cost assumption, 3) electrolyzers' access to grid service markets, 4) increased threshold price in metals industry, & 5) competition for biomass resource

Economic Potential Results



The economic potential of hydrogen demand in the U.S. is 1.4-4X current annual consumption.

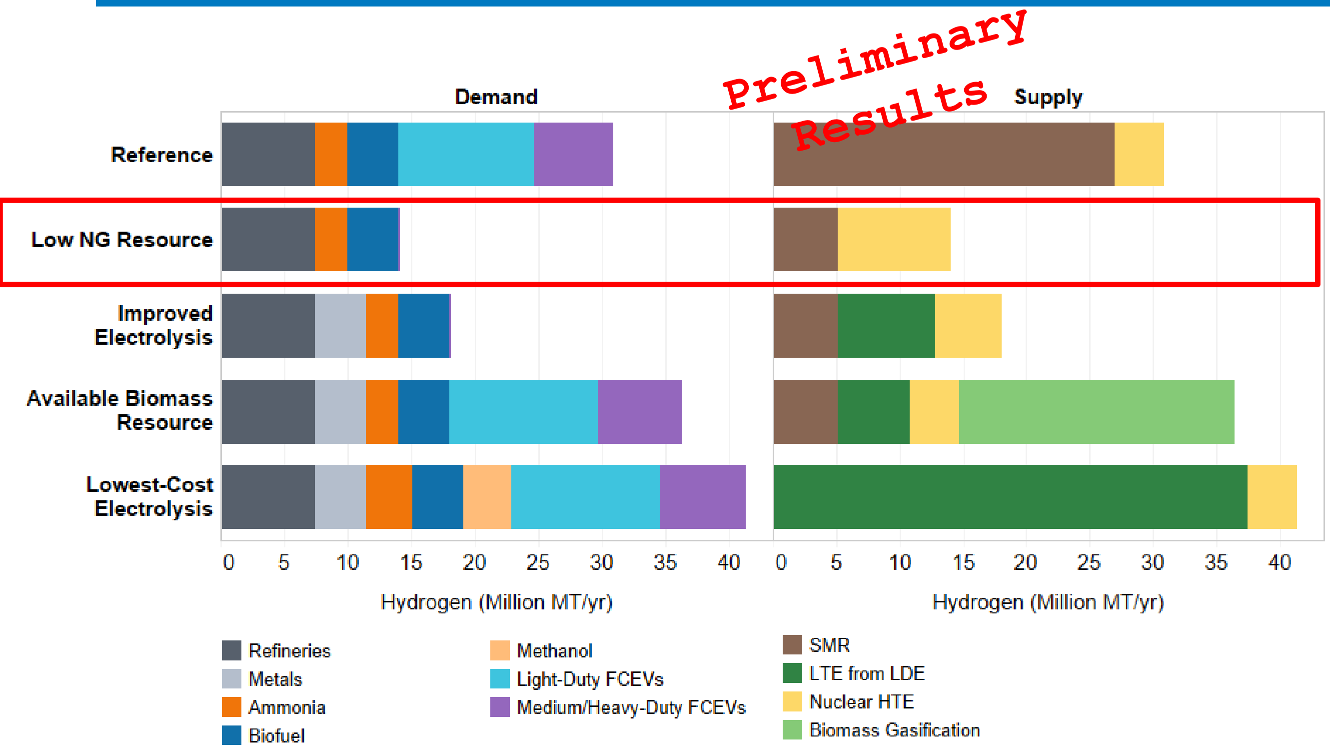
Reference Scenario



- Lowest natural gas prices; thus, higher penetrations of FCEVs
- About 10% of U.S. nuclear generation to H_2
- Refineries and ammonia demands based on growing markets
- Biofuels demand limited to Renewable Fuels Standard

FCEV: Fuel Cell Electric Vehicle

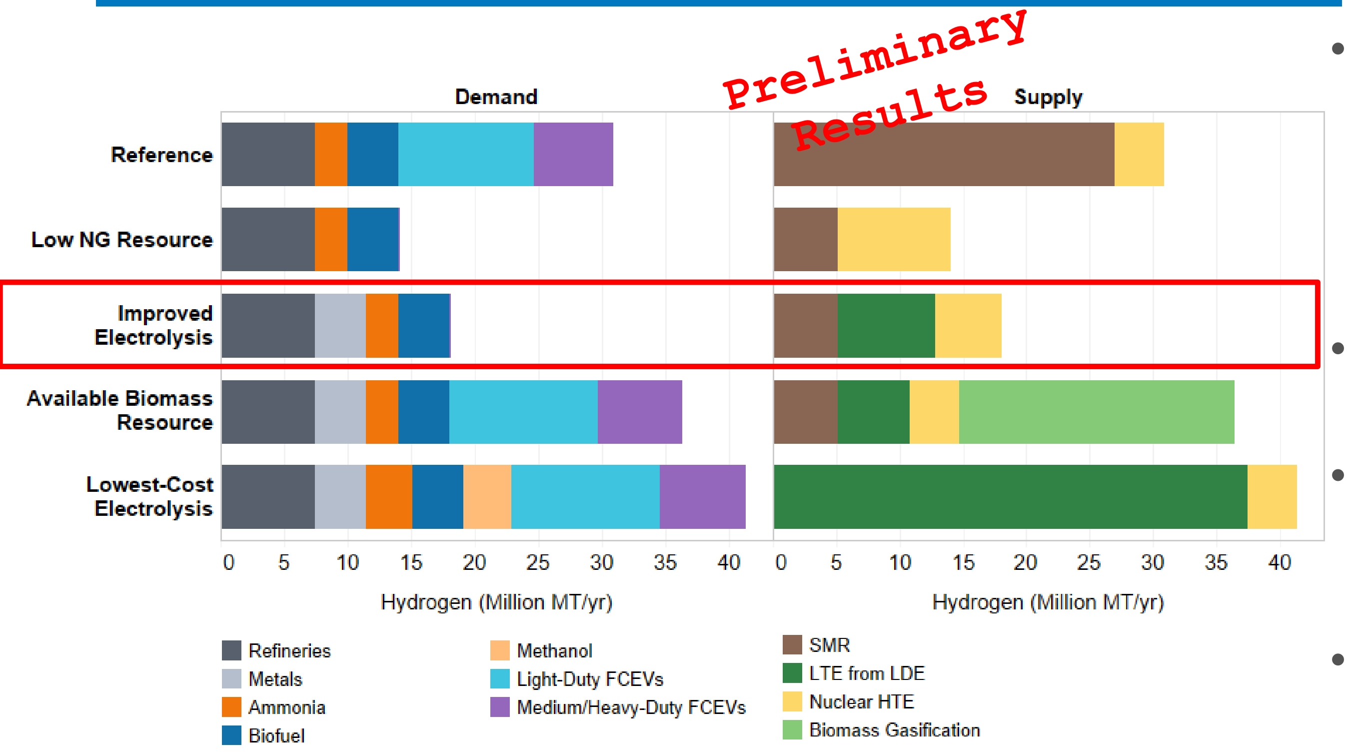
Low Natural Gas Resource Scenario



- Higher natural gas prices than reference scenario
- Thus, negligible growth in hydrogen demand
- Only economic demands: refining, ammonia, biofuels

FCEV: Fuel Cell Electric Vehicle

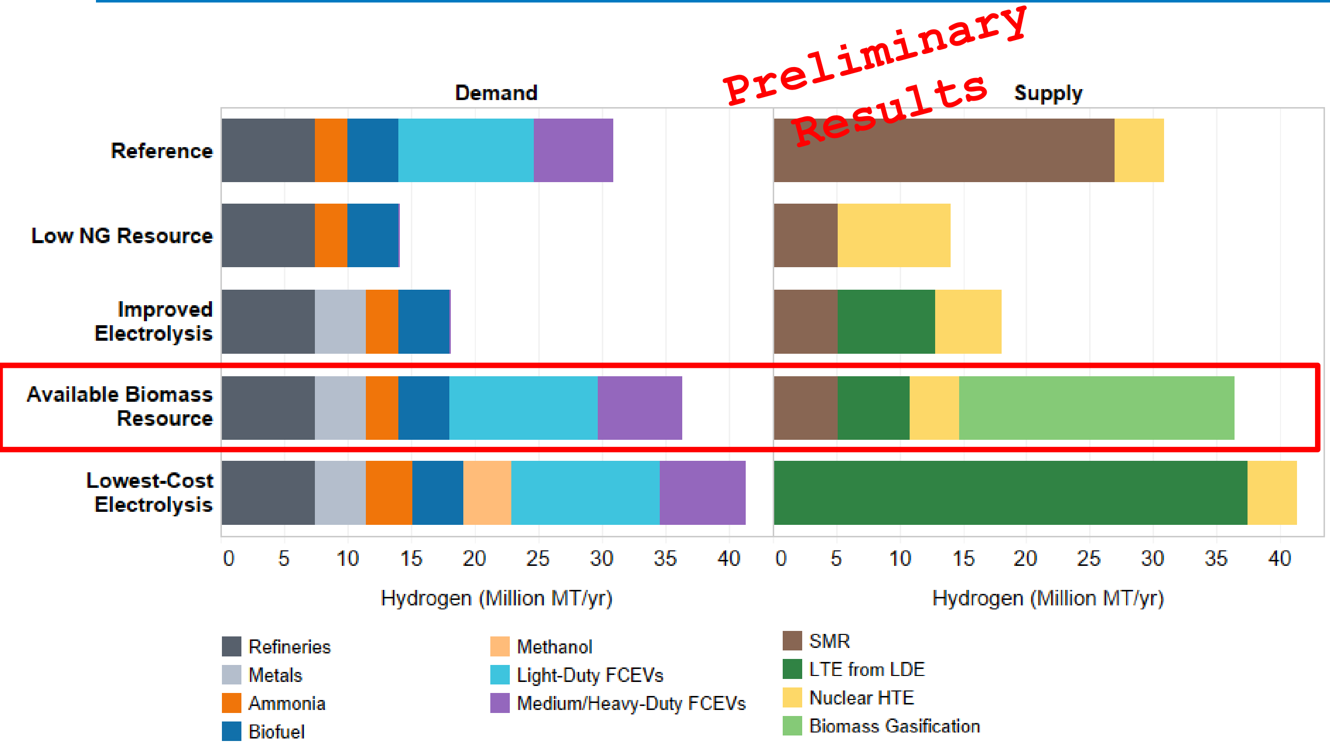
Improved Electrolysis Scenario



- **Low-Temperature electrolyzer (LTE) purchase cost reduced to $200/kW & reduced electricity price adder**
- **Supply growth due to electrolytic hydrogen**
- **Increased willingness to pay for H2 for metals refining**
- **Leads to demand for growing domestic metals refining industry**

FCEV: Fuel Cell Electric Vehicle

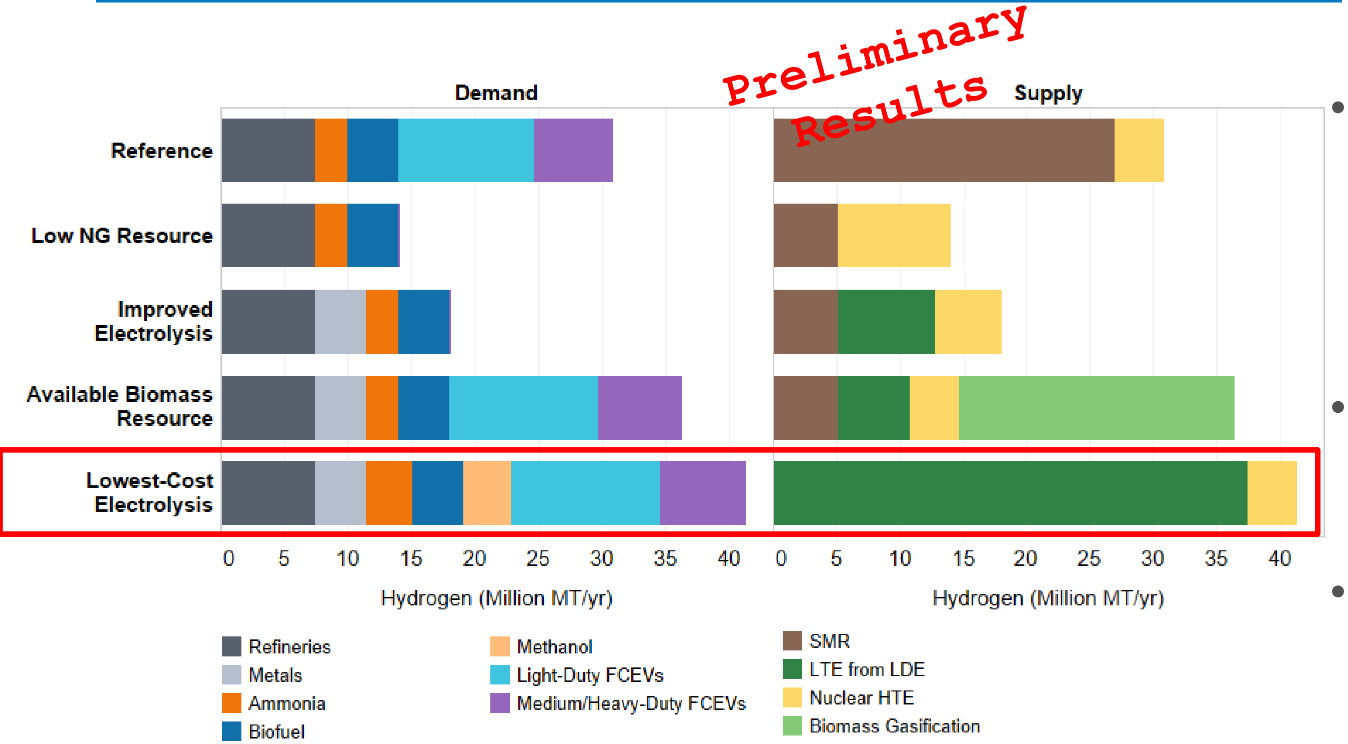
Available Biomass Resource Scenario



- Only scenario with biomass available for hydrogen production
- Lowest cost biomass resource assumed available
- Lower cost hydrogen allows demand growth

FCEV: Fuel Cell Electric Vehicle

Lowest-Cost Electrolysis Scenario

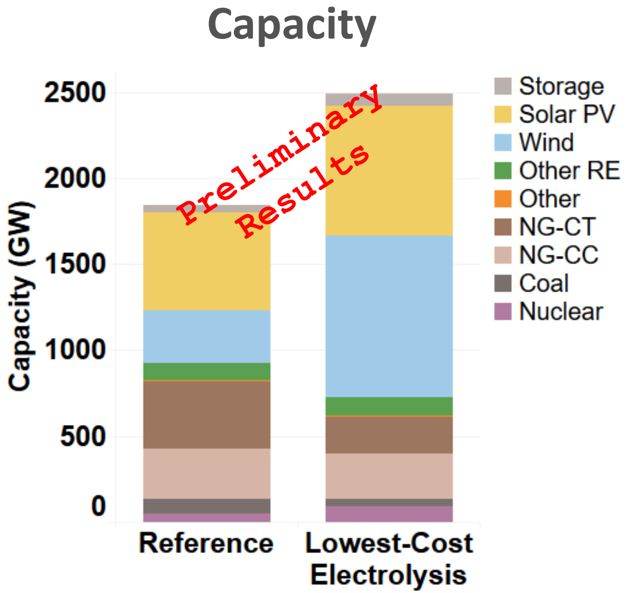


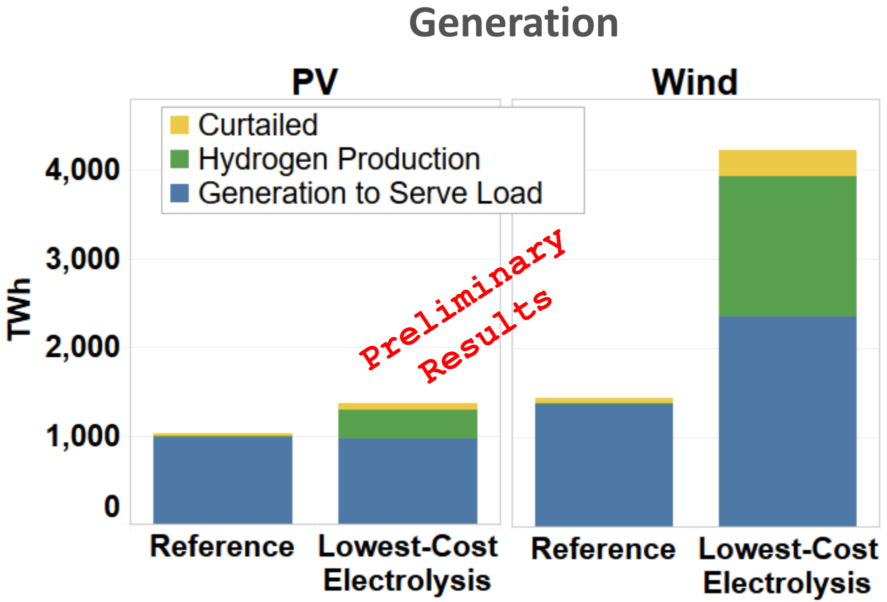
- Low-Temperature electrolyzer (LTE) purchase cost reduced to $100/kW & no electricity price adder
- Electrolytic hydrogen less costly than steam methane reforming
- Larger ammonia and chemicals opportunities than other scenarios

FCEV: Fuel Cell Electric Vehicle

Potential Impact of H2@Scale on Wind and Solar PV Markets

Hydrogen is a potential dispatchable load that can increase economic demand for variable electricity





- **Estimates are based on national scenarios with minimal resolution into regional constraints.**
- **Lowest-Cost Electrolysis assumes aggressive electrolyzer costs ($100/kW)**

Concluding Thoughts

- Energy requirements are getting more complex and H2@Scale is a potential opportunity
- **The potential demand of hydrogen demand in the U.S. is >9X current annual consumption.**
- **The economic potential of hydrogen demand in the U.S. is 1.4-4X current annual consumption**.
- Up to 20% of current **nuclear power plants could improve their profitability** by producing hydrogen.
- At high penetrations, the H2@Scale concept could increase PV penetration by about 30% and almost double wind generation

Thank You

Mark.Ruth@nrel.gov

www.nrel.gov

NREL/PR-6A20-75422

Additional information on H2@Scale can be found at:

https://www.hydrogen.energy.gov/pdfs/review18/h2000_pivovar_2018_o.pdf
https://www.hydrogen.energy.gov/pdfs/review19/sa171_ruth_2019_o.pdf
http://energy.gov/eere/fuelcells/downloads/h2-scale-potential-opportunity-webinar

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