H2NEW Hydrogen from Next-generation Electrolyzers of Water
U.S. DEPARTMENT OF ENERGY

H2 Production Economics From Electrolysis: Impact of Electricity and Capital Costs

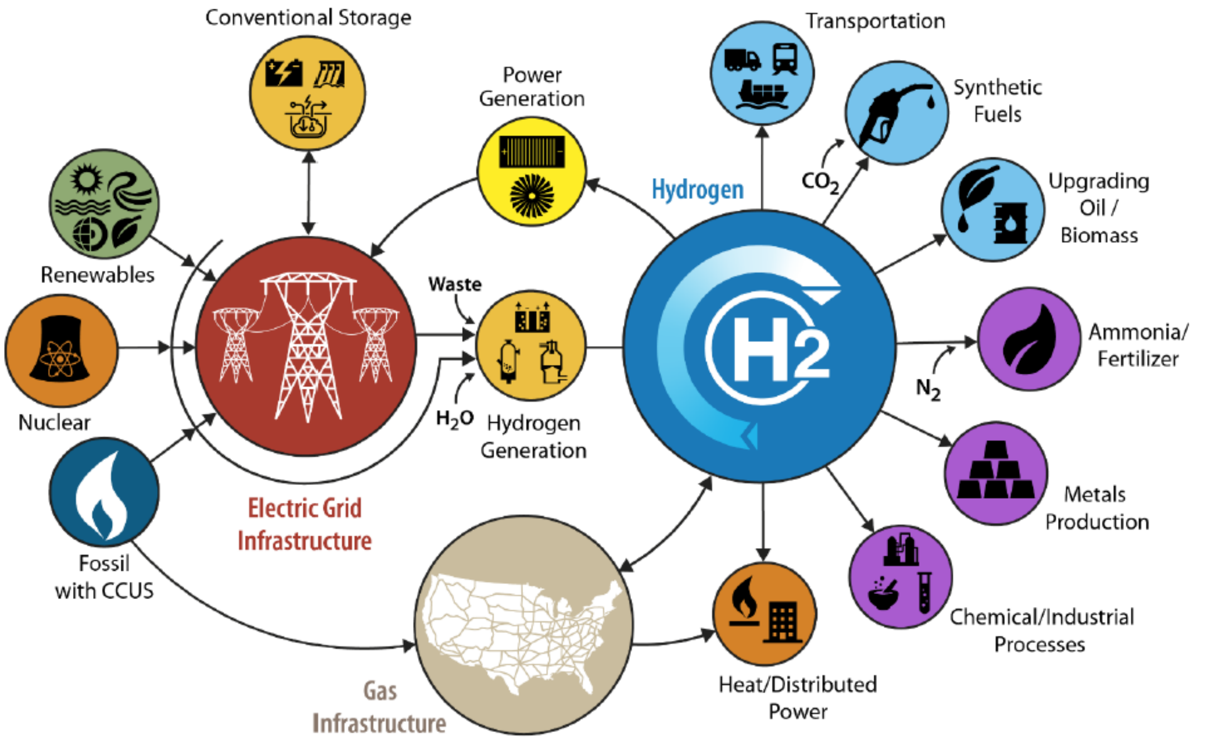
Bryan Pivovar, National Renewable Energy Laboratory (NREL)

November 20, 2024

Stark College

NREL Transforming ENERGY · INL Idaho National Laboratory · Argonne National Laboratory · Berkeley Lab Bringing Science Solutions to the World · Lawrence Livermore National Laboratory · Los Alamos National Laboratory Est. 1943 · National Energy Technology Laboratory · Oak Ridge National Laboratory · Pacific Northwest National Laboratory

H2@Scale



Illustrative example, not comprehensive

https://www.energy.gov/eere/fuelcells/h2-scale

Economics of Electrolysis

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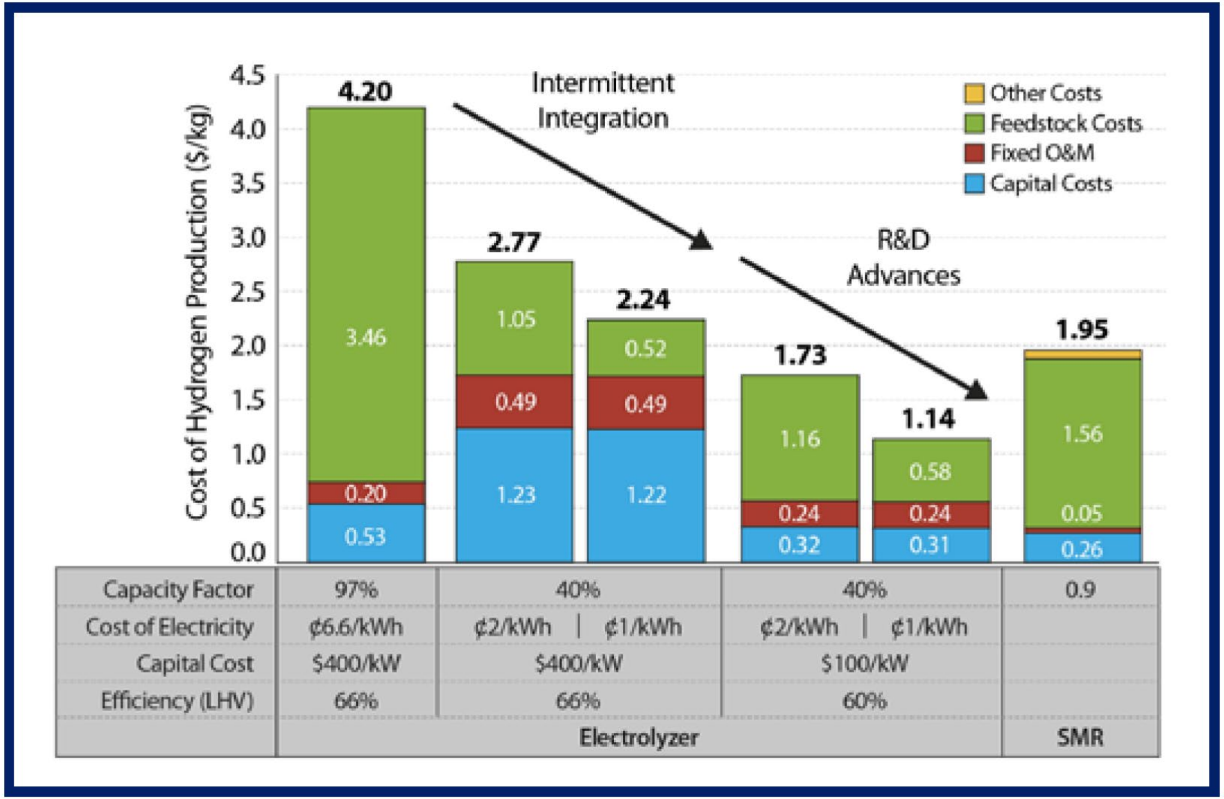


Fig. 3. *Techno-economic analysis of electrolyzer-based hydrogen production costs as a function of capacity factor, cost of electricity, capital cost, and efficiency compared to steam methane reforming (SMR), using H2A models.*[28]

Target is Hydrogen Levelized Cost and H_2 Shot targets ($2/kg in 2026, $1/kg in 2031)

2 main cost drivers
- Electricity prices
- Capital costs

At 50kWh/kg, 2¢/kWh = $1/kg

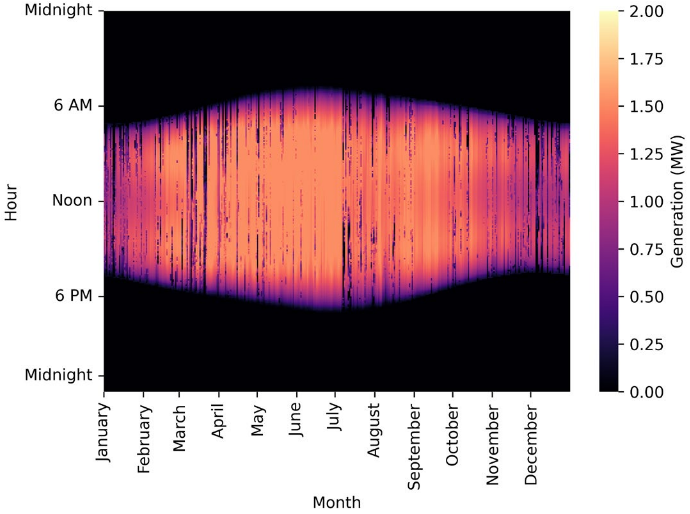
Need
- cheap electrons
- low capital cost

O&M is also important, but less understood

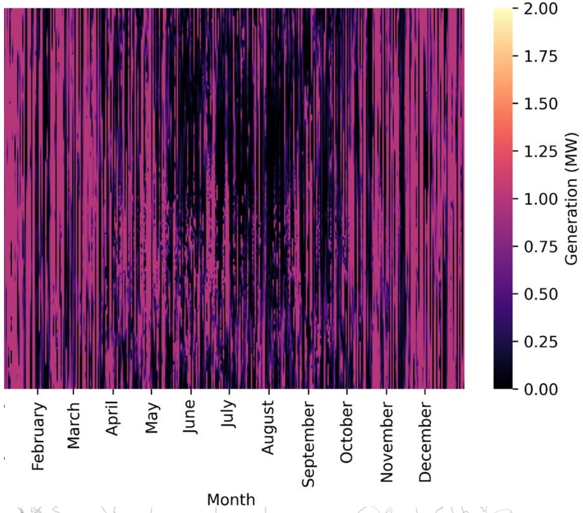
Bryan Pivovar, Neha Rustagi, Sunita Satyapal, Electrochem. Soc. Interface Spring 2018 27(1): 47-52; doi:10.1149/2.F04181if

Solar, Wind and Wind/Solar Electricity Generation

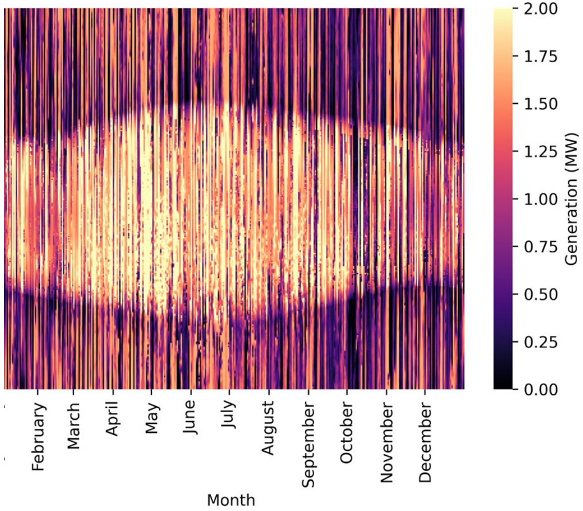
1 MW PV, Daggett, CA

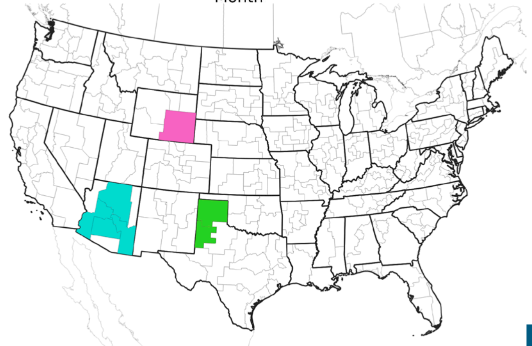


1 MW wind, Casper, WY



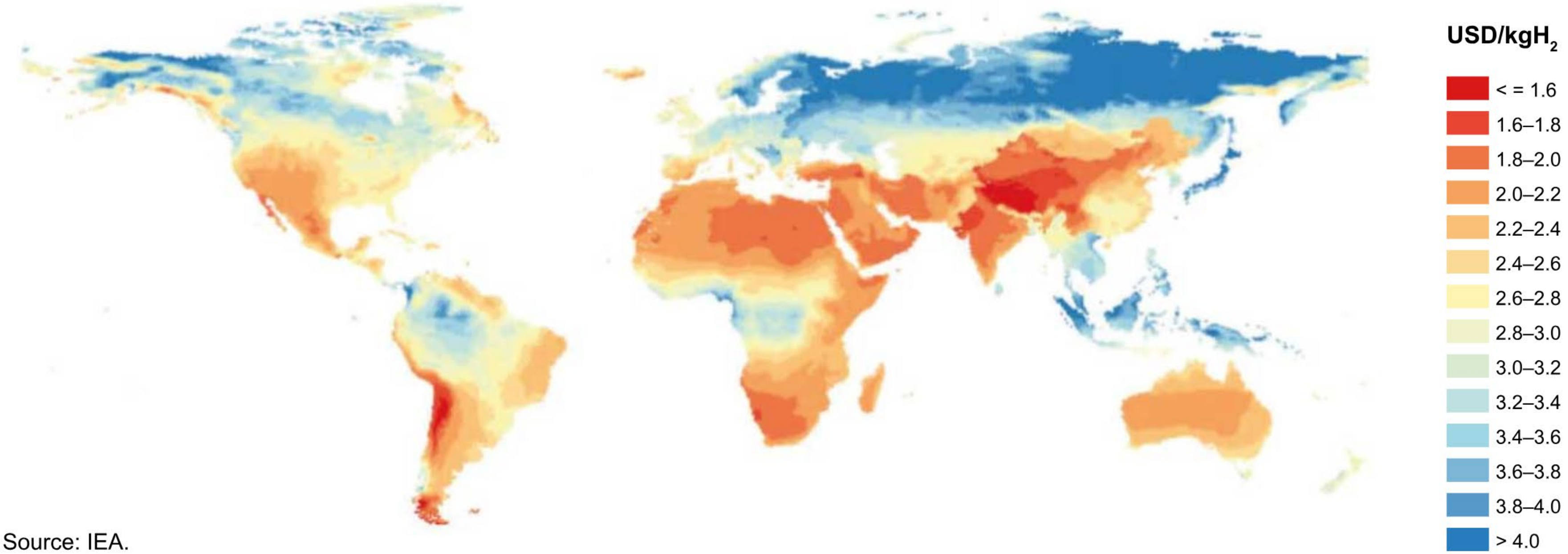
1 MW wind + 1 MW PV, Amarillo, TX





Where will H2 be made most economically

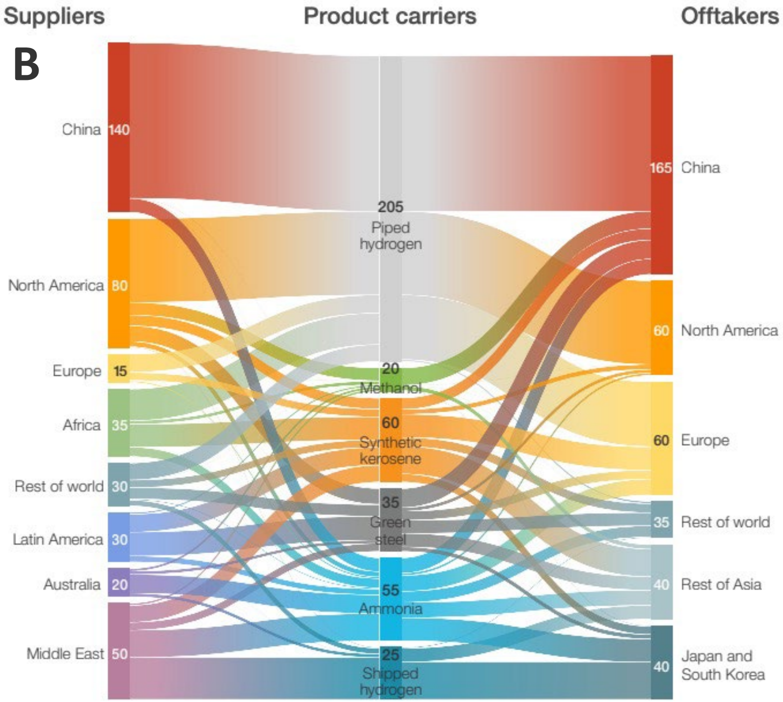
Hydrogen costs from hybrid solar PV and onshore wind systems in the long term.



Source: IEA.

Energy flows of H2

Global hydrogen and derivative interregional long-distance supply,[1] million tons per annum



1. Excludes local production and distribution.

0

Source: H2 Council

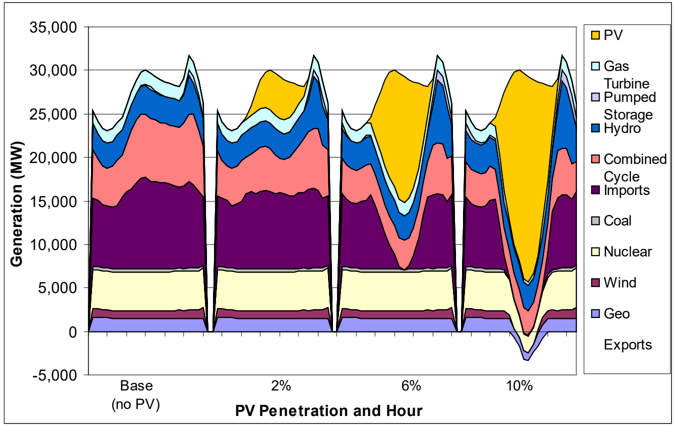
Energy System Challenges

- **Multi-sector requirements**
  - Transportation
  - Industrial
  - Grid

Over half of U.S. CO_2 emissions come from the industrial and transportation sectors

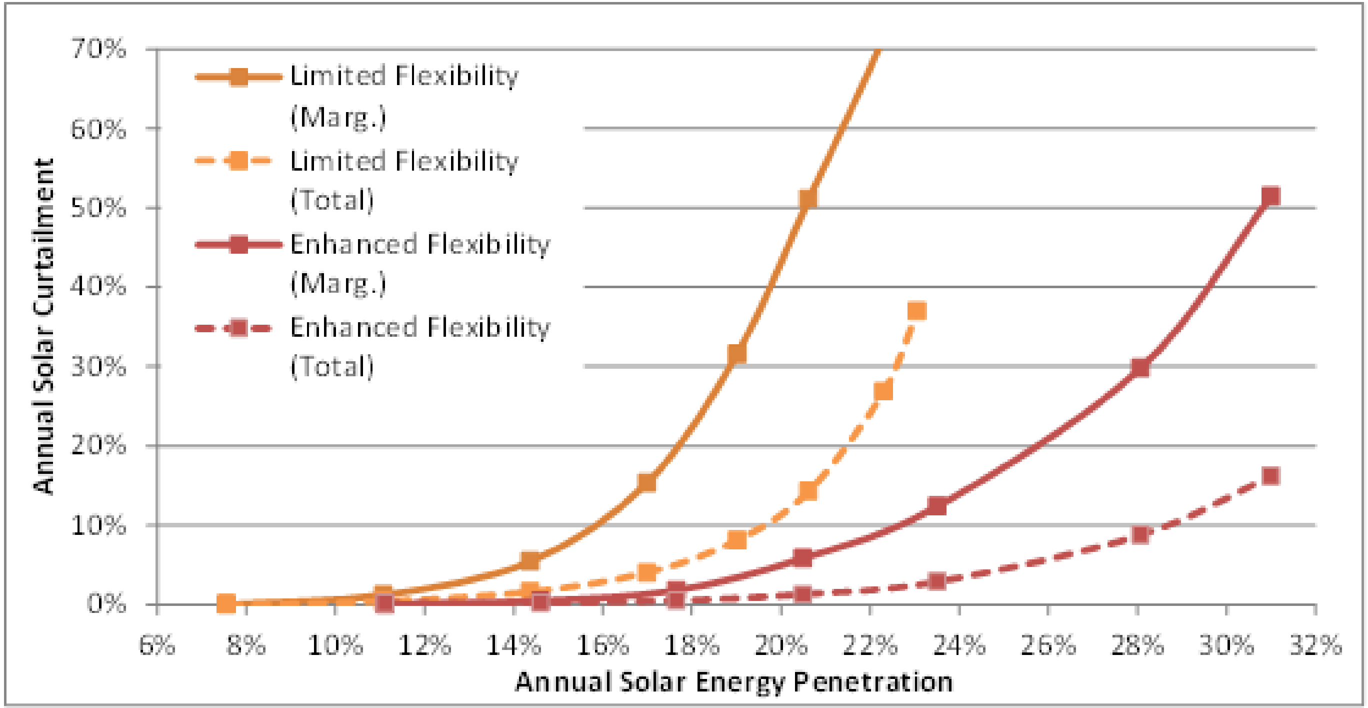
- **Renewable challenges**
  - Variable
  - Concurrent generation

Denholm et al. 2008



Limitations of Variable Inputs

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



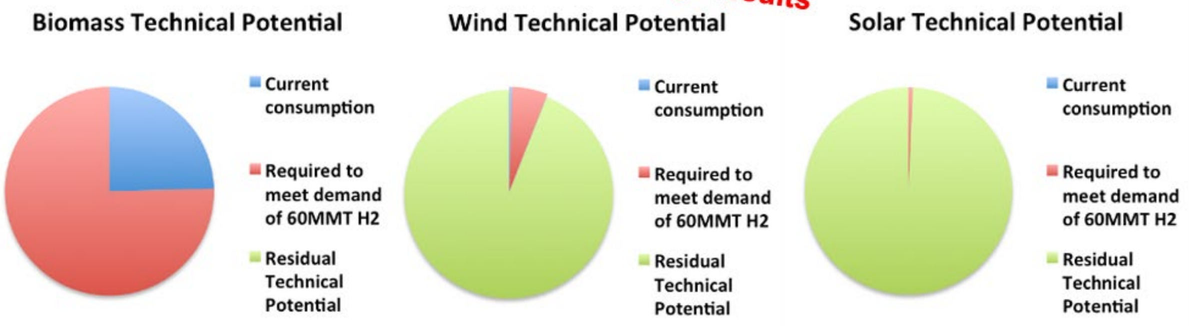
Curtailment will lead to an abundance of low value electrons, and we need solutions that will service our multi-sector demands

Future energy system will be driven by wind and solar

Accomplishment: Utilization of Renewable Resources

	EIA 2015 current consumption (quads/yr)	Required to meet demand of 60 MMT / yr (quads/yr)	Technical Potential (quads/yr)
Solid Biomass	4.7	15	20
Wind Electrolysis	0.7	9	170
Solar Electrolysis	0.1	9	1,364

Preliminary Results



Total demand including hydrogen is satisfied by ≈6% of wind, <1% of solar, and ≈100% of biomass technical potential

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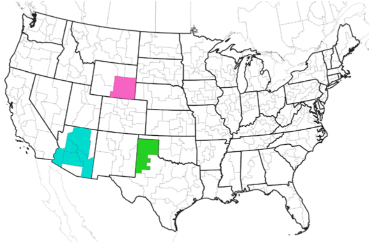
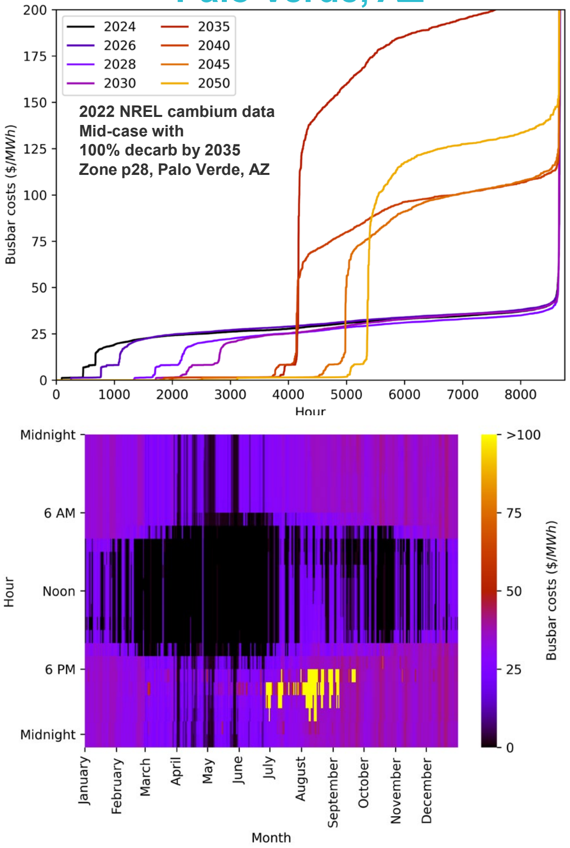
https://www.hydrogen.energy.gov/docs/hydrogenprogramlibraries/pdfs/review17/tv045_ruth_2017_o.pdf

Renewable Electricity

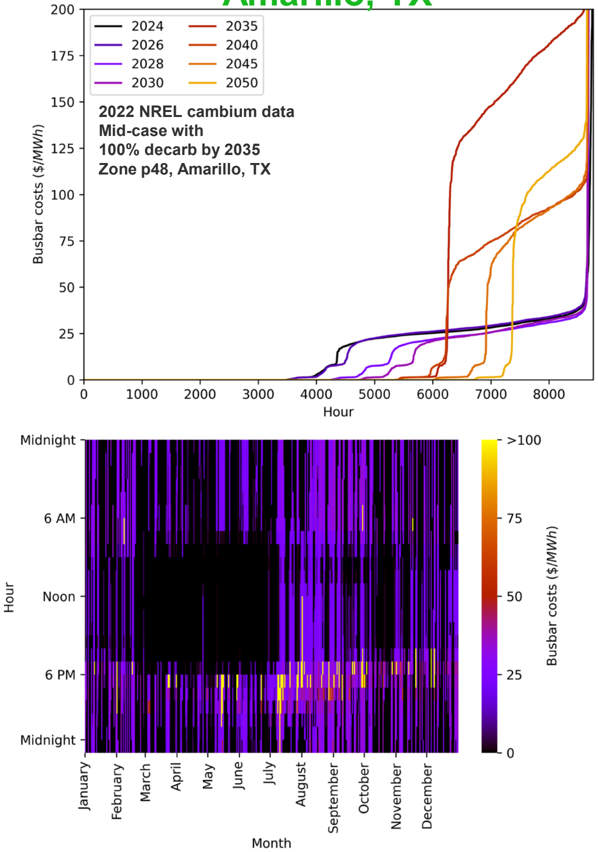
Analysis of projected marginal electricity costs by location



Palo Verde, AZ



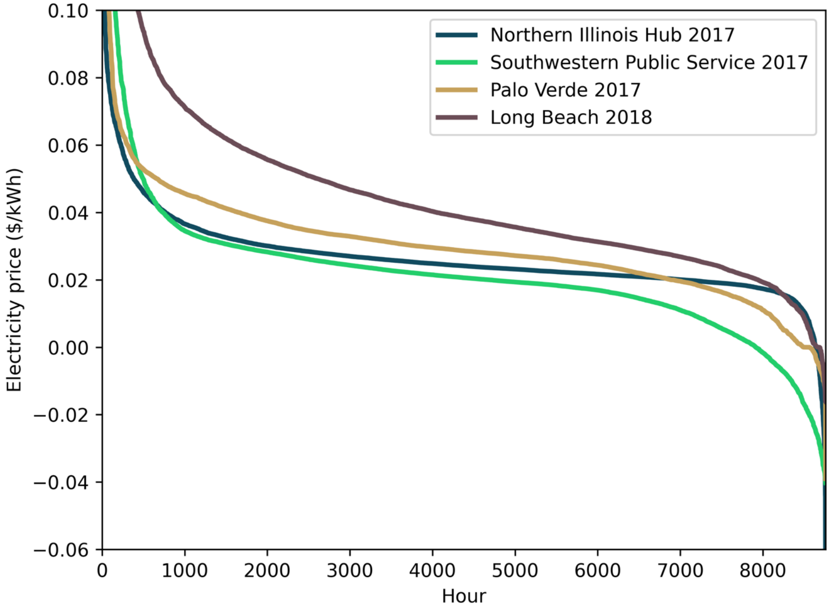
Amarillo, TX



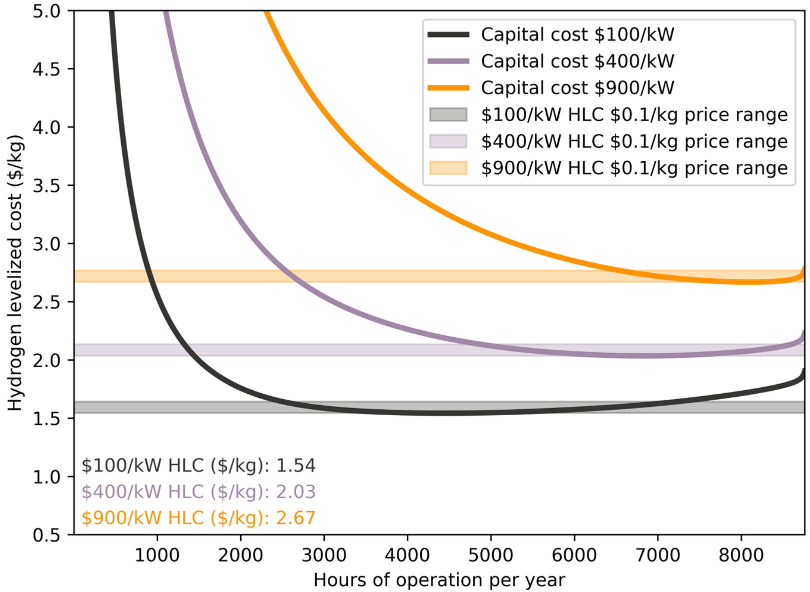
- Price structures directly influence optimal operating strategies.
- Explores the impact of “chasing” cheap electricity.
- Ignores the impact that electrolysis can have on electricity price structure.

Badgett A, Saha P, Brauch J, Pivovar B. SUBMITTED: Decarbonization of the electric power sector and implications for low-cost hydrogen production from water electrolysis 2023;Advanced Sustainable Systems.

Accomplishment: Hydrogen cost impacts



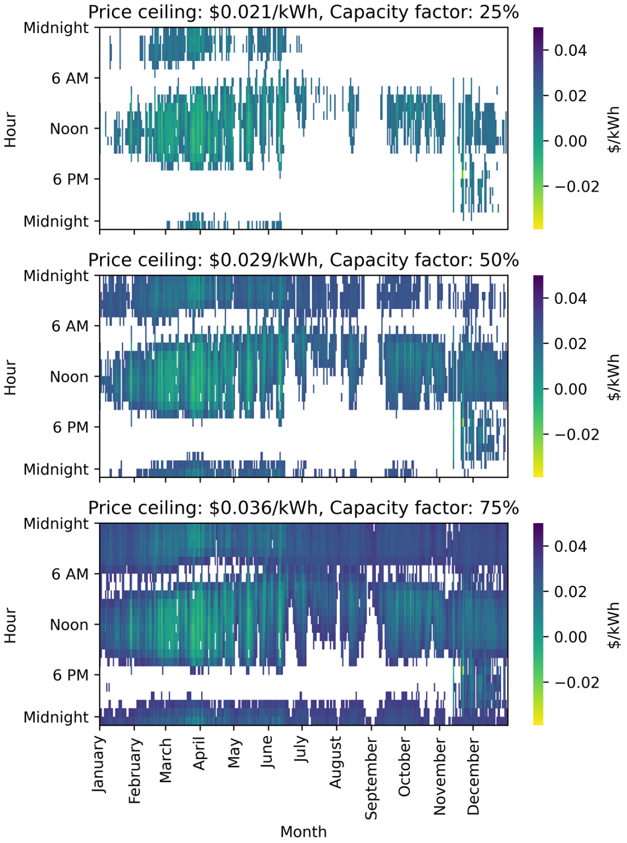
Location Marginal Pricing (LMP) for electricity can be used to explore operating strategies



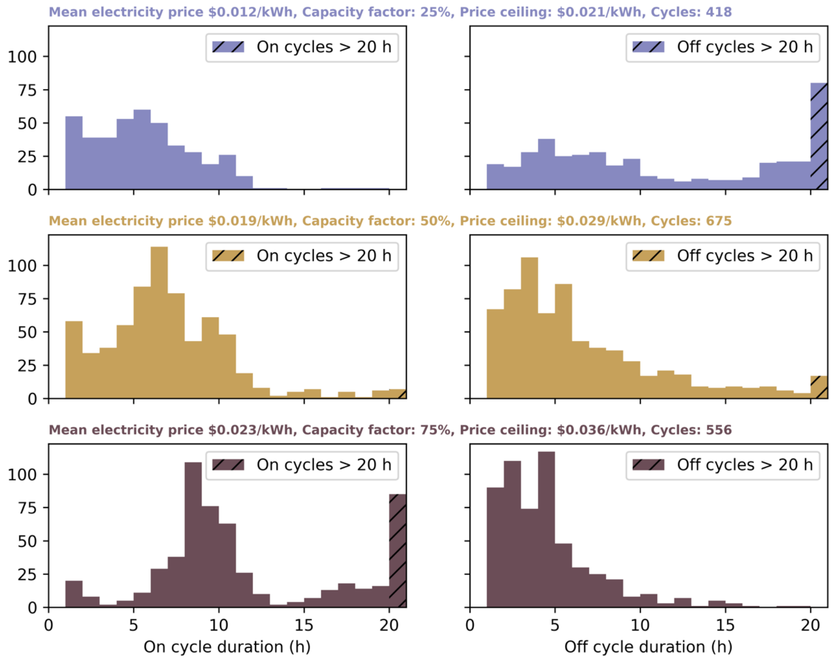
Both capital costs and electricity prices critical to HLC.

Alex Badgett, Mark Ruth, Bryan Pivovar, "Economic considerations for hydrogen production with a focus on polymer electrolyte membrane electrolysis," Electrochemical Power Sources: Fundamentals, Systems, and Applications, 2022, 327-364. https://doi.org/10.1016/B978-0-12-819424-9.00005-7

Accomplishment: Duty cycle implications for ASTs



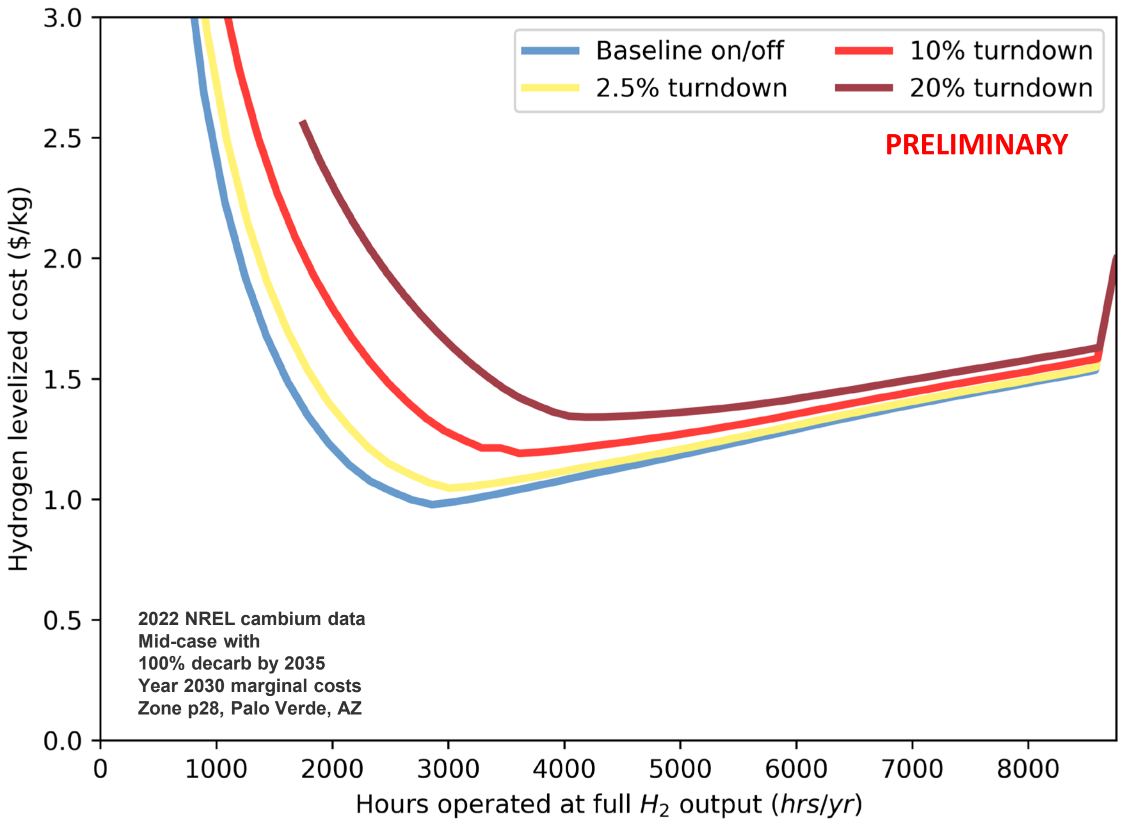
LMP heatmaps can give insight into potential operating strategies



On-off cycle duration and frequency can help support AST development.

Optimized operating and deployment strategies

- Today electrolyzers operate 24/7 at rated output
  - can't chase cheap electrons or balance the energy system
  - over-engineered for expensive electrons
  - Risk mitigation for durability
- Start-stop vs. Idle
- Has different impacts/capabilities depending on electrolyzer type/ electrocatalysts



Improving the economics of H2@Scale

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Early-stage research is required to evolve and de-risk the technologies.

MAKE

Hydrogen production technologies

MOVE

Hydrogen storage, compression, and distribution, and thermal integration

USE

Hydrogen end use technologies and demand

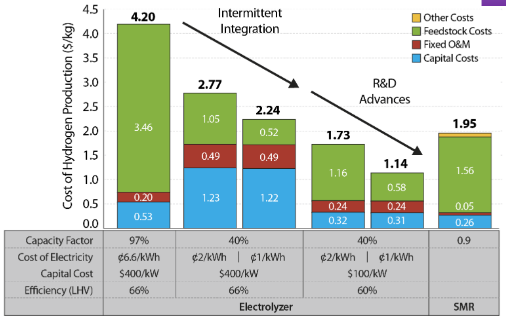
Preliminary

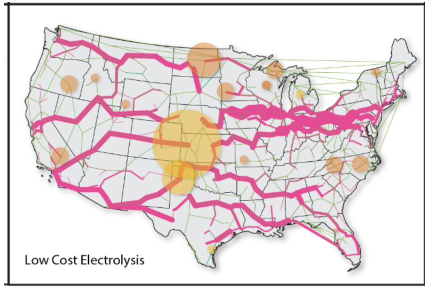
Use	Potential MMT/yr
Refineries & CPI	8
Metals	12
Ammonia	4
Synthetic Chemicals	14
Biofuels	1
Natural Gas	10
Light Duty Vehicles	57
Other Transport	17
Electricity Storage	28
Total	**151**

STORE

Improved Bulk Storage Technologies

Decreasing cost of H_2 production





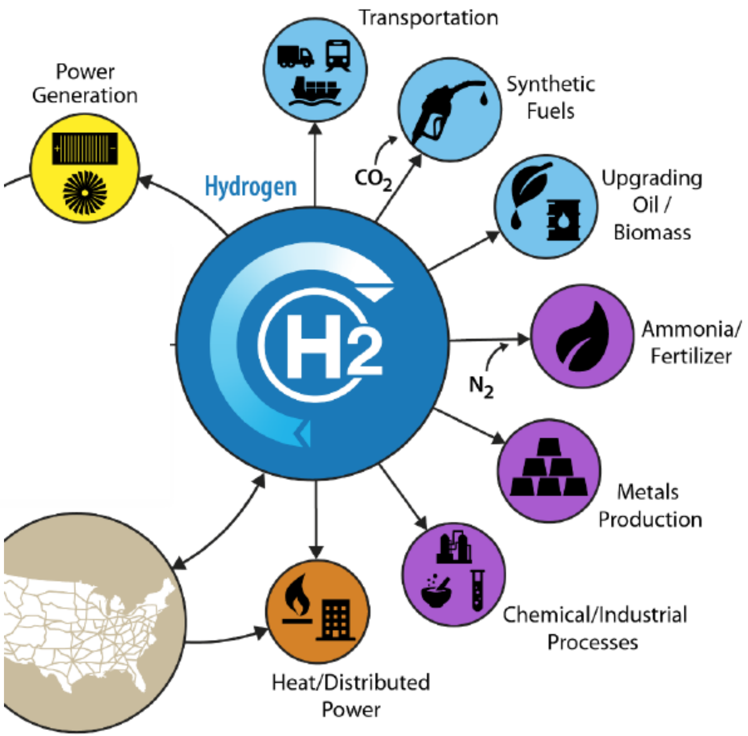
Optimizing H_2 storage and distribution

Leveraging of national laboratories' early-stage R&D capabilities needed to develop affordable technologies for production, delivery, and end use applications.

https://www.hydrogen.energy.gov/pdfs/review18/tv045_ruth_2018_o.pdf

Use

Use



https://www.energy.gov/eere/fuelcells/h2-scale

https://www.nrel.gov/docs/fy21osti/77610.pdf

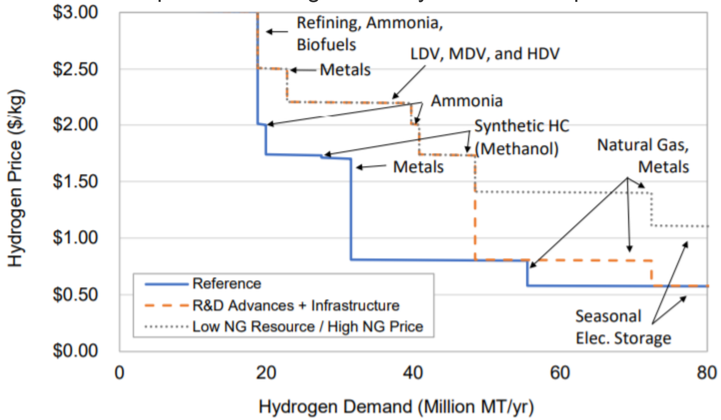


Figure 24. Aggregated demand curves for H2@Scale scenarios

- Transportation and Industry are strongest economic sectors (also difficult to decarbonize)
- Many of the processes are or could be electrochemical
- Difficult or impossible to fully electrify
- R&D needs are significant
  - Fuel Cells (M2FCT), NH3, Steel, burners/turbines

Move/Store

Energy Transmission Infrastructure

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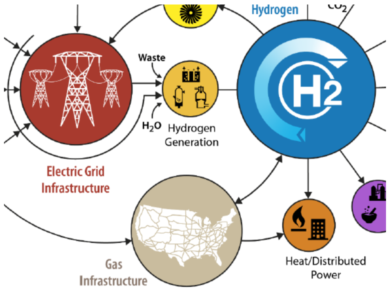
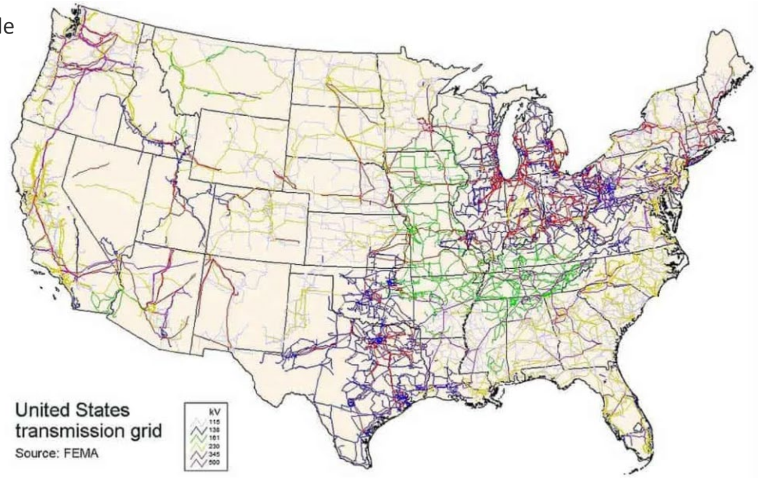
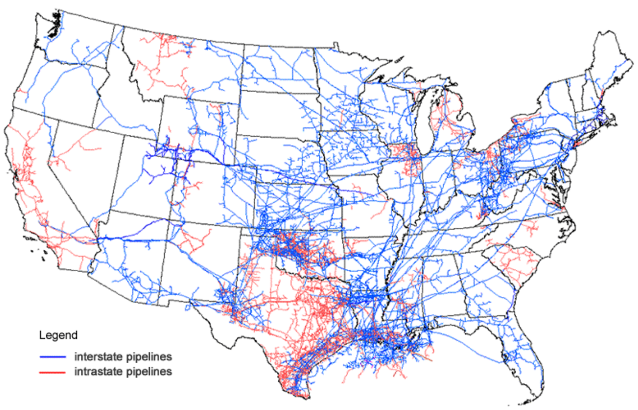
https://www.energy.gov/eere/fuelcells/h2-scale





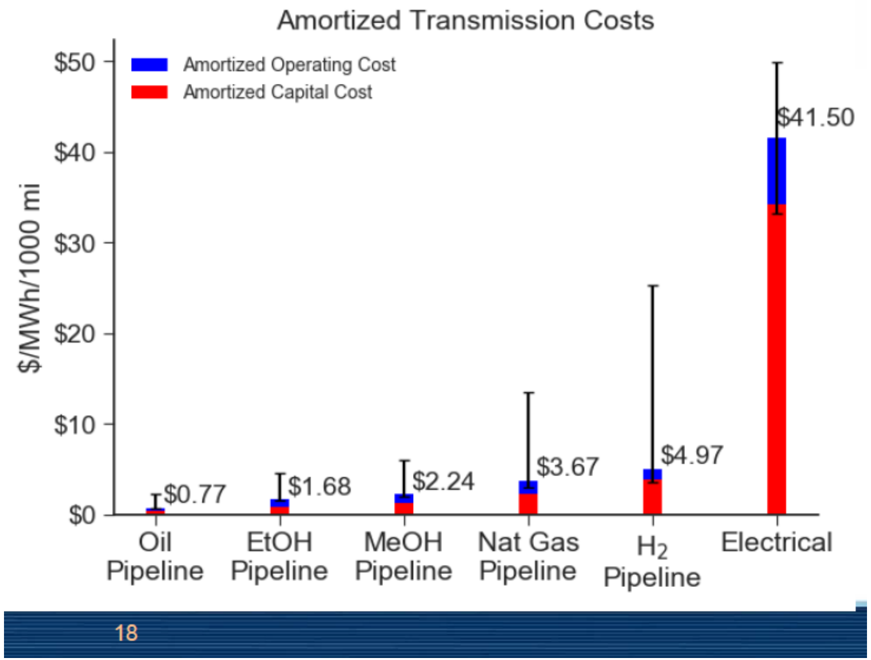
Map of U.S. interstate and intrastate natural gas pipelines



Source: U.S. Energy Information Administration, *About U.S. Natural Gas Pipelines*

- Hydrogen has a very limited infrastructure (due to scale and selective use).
  - Current H2 prices dominated by storage and distribution (LDV CA)
- Electricity and natural gas have extensive infrastructural investments.
- Similar maps, much different energy/cost, permitting challenges
- Hydrogen pipeline analogous to natural gas

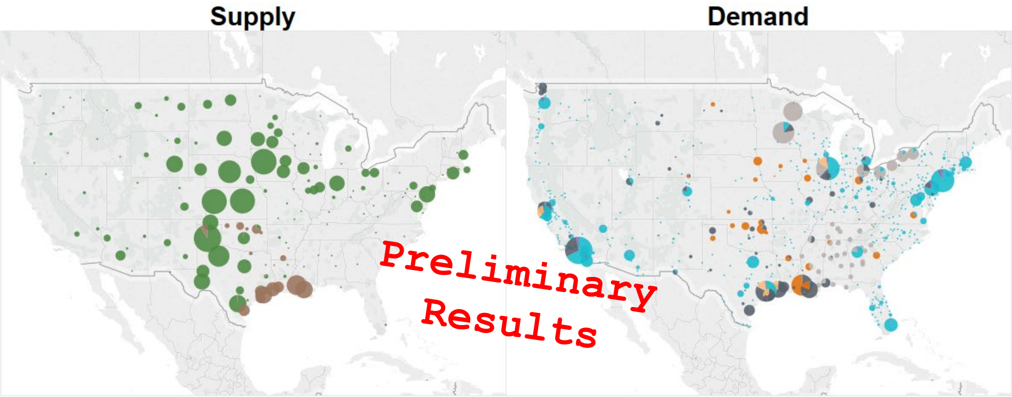
Natural gas as the nearest H2 parallel

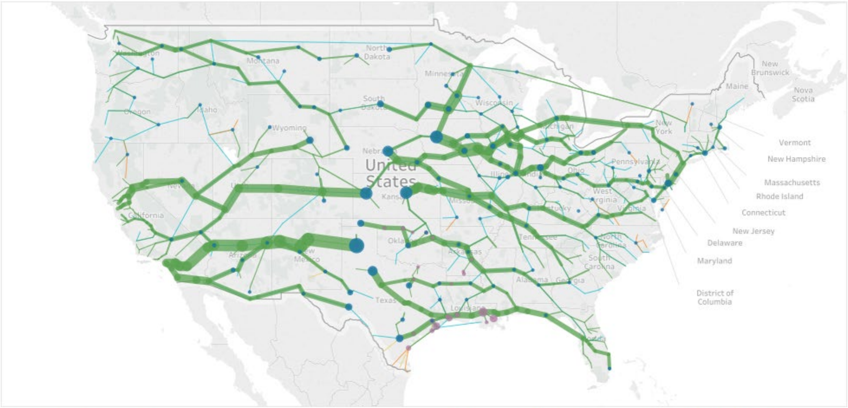


- Hydrogen perhaps ~30% move expensive to move than natural gas.
- ~1/3rd volumetric energy density, ~1/3rd viscosity.
- Additional materials compatibility limitations
- Particularly relevant at large scales and long distances

https://www.hydrogen.energy.gov/pdfs/review18/pd102_james_2018_p.pdf

Location of Generation vs. Demand





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https://www.hydrogen.energy.gov/pdfs/review18/tv045_ruth_2018_o.pdf

Make

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H2NEW : H2 from Next-generation Electrolyzers of Water

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A comprehensive, concerted effort focused on overcoming technical barriers to enable affordable, reliable & efficient electrolyzers to achieve <$2/kg H_2

- Launched in Oct 2020
- FY 21, 22: $10M/yr (PEM 75%, o-SOEC 25%)
- FY 23-2?: $28M/yr ($12M PEM, $6M Liquid Alkaline, $10M O-SOEC)

National Lab Consortium Team

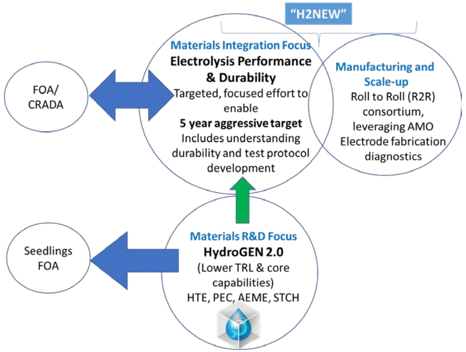
NREL – National Renewable Energy Laboratory
INL – Idaho National Laboratory
Argonne National Laboratory
Berkeley Lab
Pacific Northwest National Laboratory
Los Alamos National Laboratory
Lawrence Livermore National Laboratory
Oak Ridge National Laboratory
NETL – National Energy Technology Laboratory

Clear, well-defined stack metrics to guide efforts.

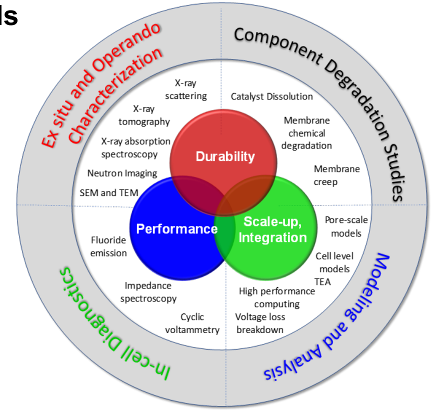
Draft Electrolyzer Stack Goals by 2025

	LTE PEM	HTE
Capital Cost	$100/kW	$100/kW
Elect. Efficiency (LHV)	70% at 3 A/cm^2	98% at 1.5 A/cm^2
Lifetime	80,000 hr	60,000 hr

Leverages and connects to other DOE efforts



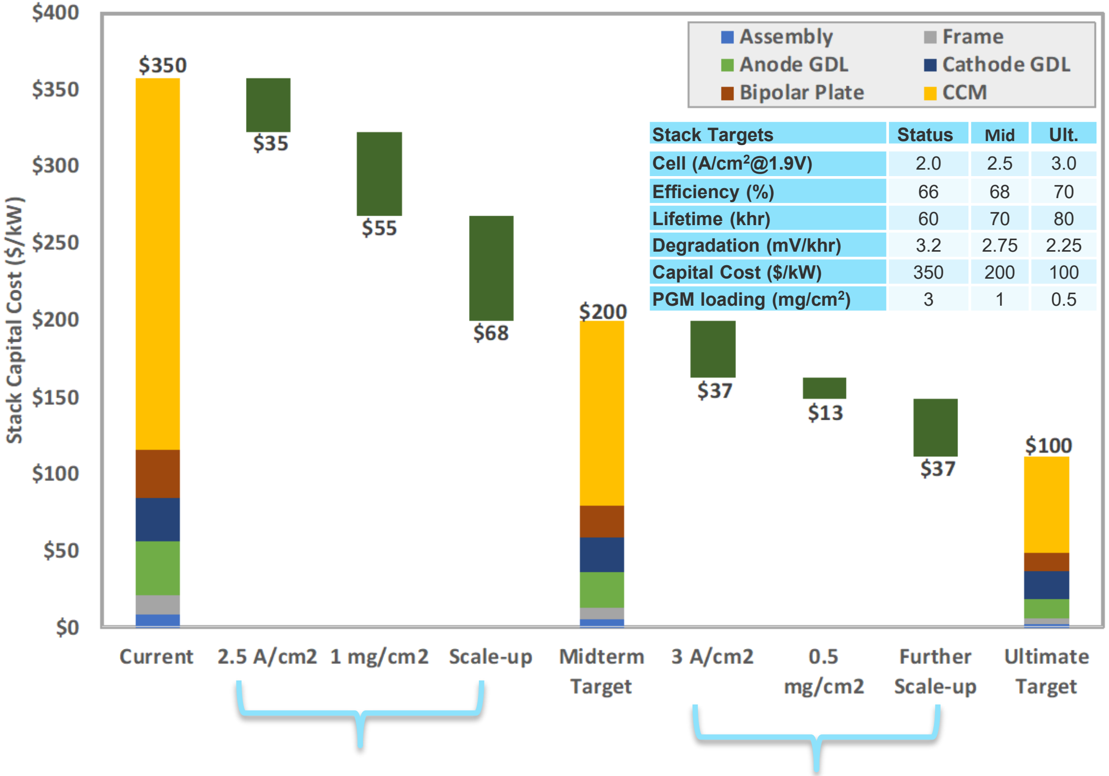
Utilize combination of world-class experimental, analytical, and modeling tools



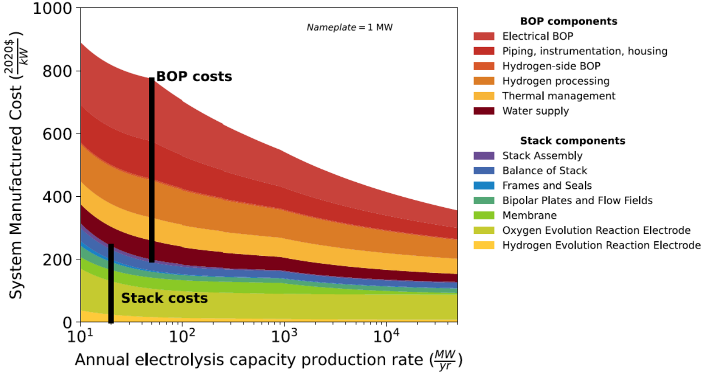
Durability/lifetime is most critical, initial, primary focus of H2NEW

- Limited fundamental knowledge of degradation mechanisms, under appropriate operating strategies.
- $450M in electrolysis FOA awards under negotiation, much of which will be supported by H2NEW core lab team.

Stack Costs (PEM Centric to date)



Stack Targets	Status	Mid	Ult.
Cell (A/cm^2@1.9V)	2.0	2.5	3.0
Efficiency (%)	66	68	70
Lifetime (khr)	60	70	80
Degradation (mV/khr)	3.2	2.75	2.25
Capital Cost ($/kW)	350	200	100
PGM loading (mg/cm^2)	3	1	0.5



Modeling of stack costs show strongest levers are:

1. Increased efficiency/ current density
2. Decreased PGM loading
3. Scale-up

Targeting Research Areas

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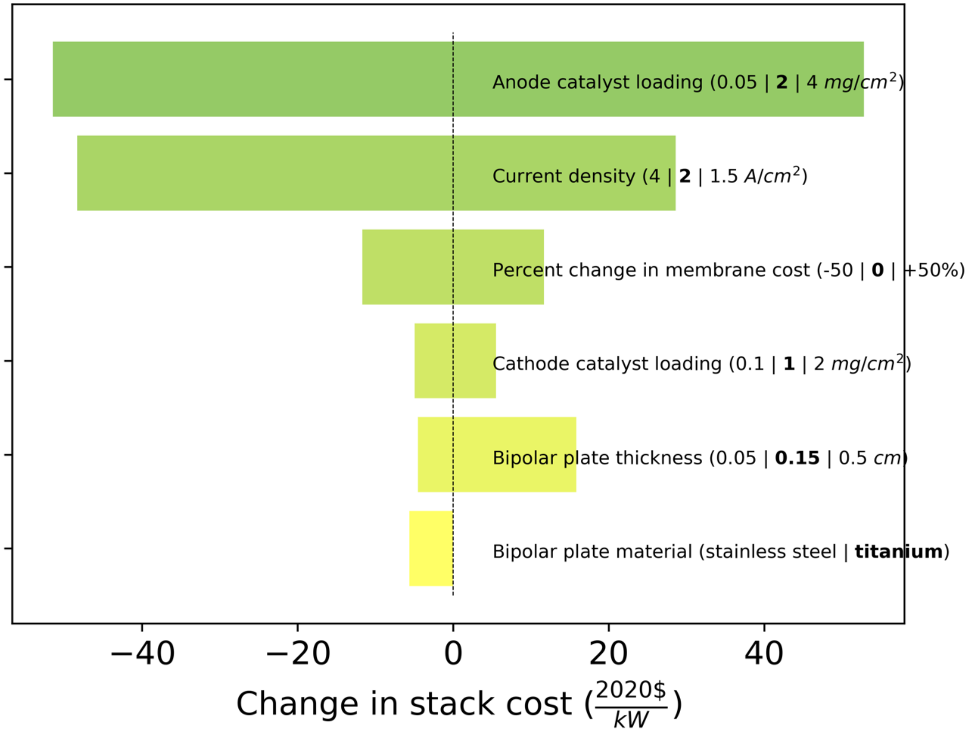
- Current density and catalyst loading are primary cost drivers
- Membrane thickness also enables increased current density
- Because low cost electrons are a requirement, lower premium is placed on efficiency.



Thank you (and others)

HTE In-Person Meeting PNNL, March 4-6, 2024

NREL Team Members: Shaun Alia, Alex Badgett, Carlos Baez-Cotto, Guido Bender, Isabell Berry, Sarah Blair, Eric Boerner, Joe Brauch, Ai-Lin Chan, Huyen Dinh, Dave Ginley, Radhika Iyer, Sunil Khandavalli, Scott Mauger, Samantha Medina, Woo Yeong Noh, Elliot Padgett, Makenzie Parimuha, Chance Parrish, Bryan Pivovar, Elias Pomeroy, Cheryl Reuben, Robin Rice, Daniela Ruiz, Meital Shviro, Sarah Shulda, Lauren Sittler, Chris Skangos, Colby Smith, Jennifer Sosh, Sam Ware, Jacob Wrubel, James Young, Jason Zack, Diana Zhang

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LBNL Team Members: Grace Anderson, Claire Arthurs, Anyka Bergeson-Kreller, Ashley Bird, Hanna Breunig, Ethan Crumlin, Arthur Dizon, , Ramachandra Gawas, Elizabeth Greenberg, Rebecca Hamlyn, Jason Keonhag Lee, Doug Kushner, Ahmet Kusoglu, Grace Lau, Eric Lees, Tamim Mohammed, Rangachary Mukundan, Xiong Peng, Paul Rudnicki, Michael Tucker, Guanzhi Wang, Adam Weber

PNNL Team Members: Jie Bao, Seraphim Belko, Chris Coyle, Dan Edwards, Julian Escobar, Michael Fuller, Jamie Holladay, Surendra Karki, Long Le, Tian Liu, Olga Marina, Matt Olszta, Sangbong Ryu, Lorraine Seymour, Renaldo Springer, Dewei Wang

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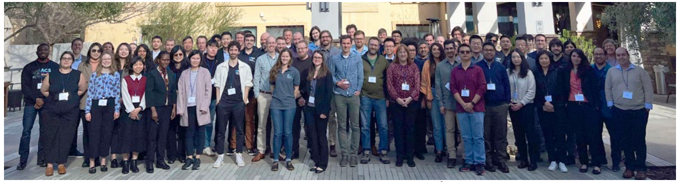
NETL Team Members: Harry Abernathy, William Epting, Yinkai Lei, Tianle Cheng, Tao Yang, Fei Xue, Greg Hackett

NIST Affiliate Team Members: Michael Daugherty, Daniel Hussey, David Jacobson, Jacob LaManna

SLAC: Nick Strange



LTE In-Person Meeting Napa, CA, February 21-23, 2024

University Collaborators: Jayson Foster, Svitlana Pylypenko (PI), Lonneke van Eijik, Max Shepherd, Genevieve Stelmacovic, Brian Gorman (CSM); Kara Ferner, Shawn Litster (PI), Fausto Pasmay (CMU); Devashish Kulkarni, Jack Todd Lang, John Stansberry, Cliff Wang, Iryna Zenyuk (PI) (UCI); Scott Barnett, Peter Voorhees (NU), Xiao-Dong Zhou (UL-L), Paul Salvador (CMU), William Kent (CMU)

ASTWG Collaborators: Kathy Ayers (Nel Hydrogen), Nemanja Danilovic (Electric Hydrogen), Corky Mittelsteadt (Plug Power), Andrew Park (Chemours), Udit Shrivastava (Cummins), Andrew Smeltz (De Nora)

Other Partnerships and Collaborations: MIT, B. Khaykovich; FZ Jülich, Germany; Fraunhofer ISE, Freiburg, Germany; Paul Scherrer Institute, Aargau, Switzerland, IEA Annex 30 Working Group; Gen-IV International Forum for Hydrogen Production (Canada, France, Japan, England, United States)