To What Extent will Decarbonization Deepen the Conversation between Industry and the Grid?

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FIPSE-6

June 19, 2024

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Agenda

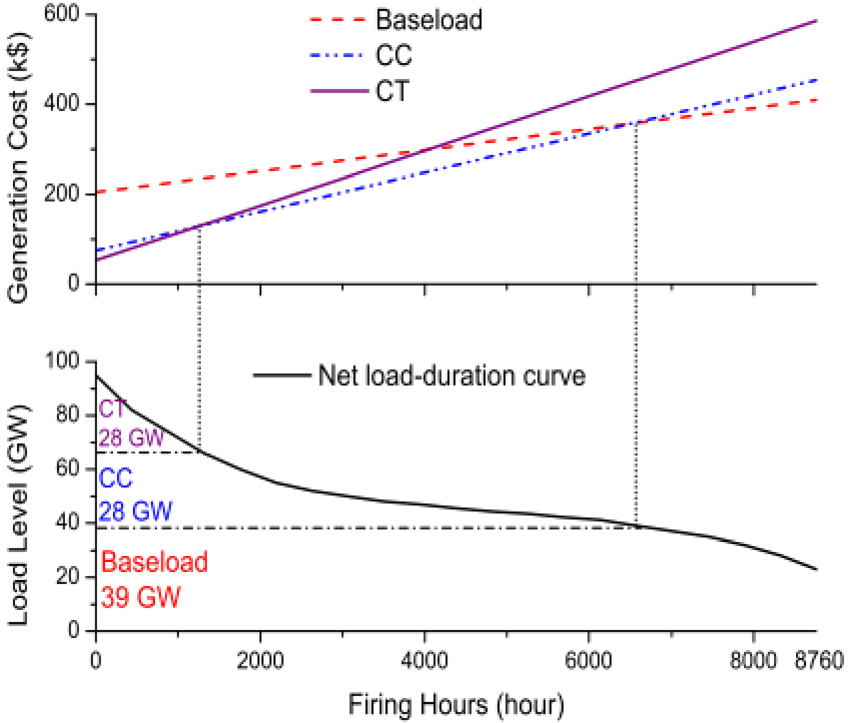
- Framing
  - Grid decarbonization
  - Industry decarbonization
  - Industry-grid interactions
- Open problems in industry-grid interactions
  - Planning
  - Operations
- Conclusions

Framing

Grid Decarbonization

Old Paradigm

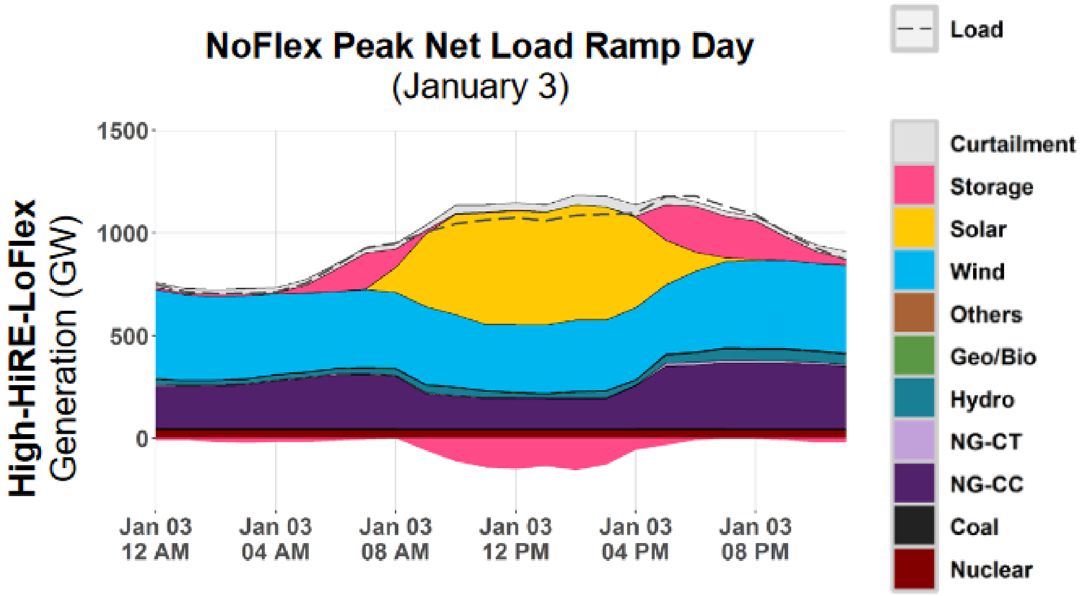
Screening Curves with Merit-Order Dispatch



(Sullivan, Eurek, and Margolis 2014; Zhang 2013)

- Large, centralized, dispatchable plants reduce key planning parameters to:
  1. Peak demand
  2. Annual energy

New Paradigm

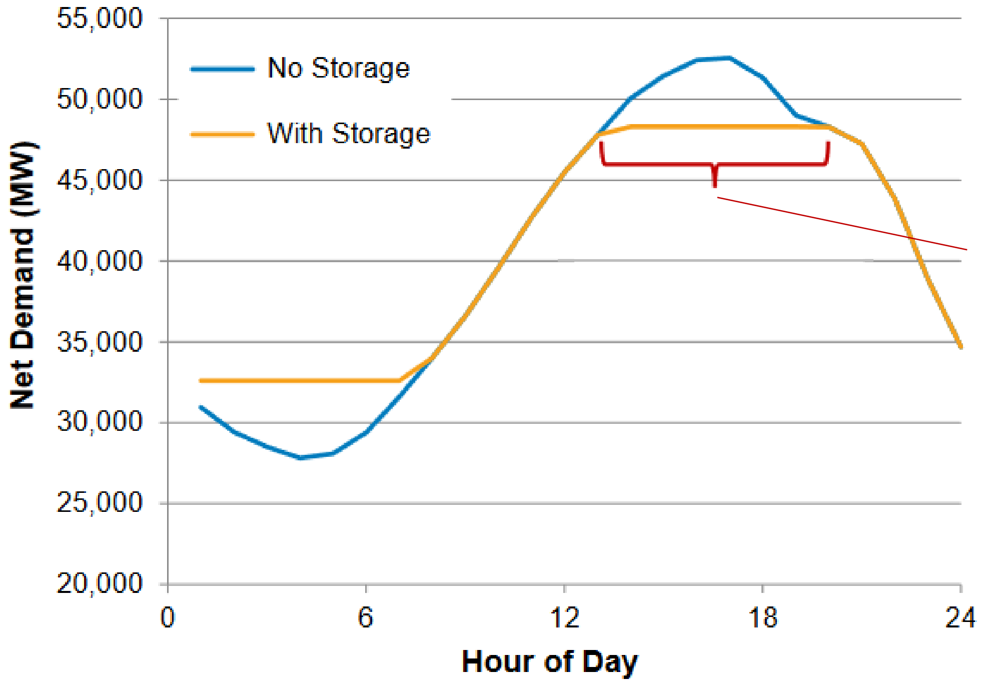


Example dispatch from one scenario-day (Zhou and Mai 2021)

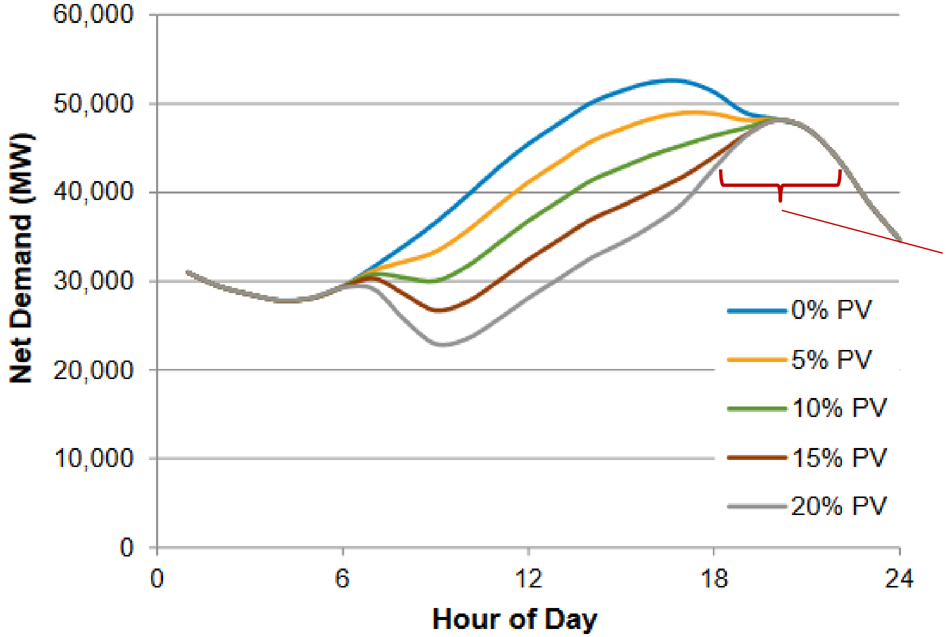
- A diversity of resources, including variable generation (VG) from wind and solar
- VG and other renewable energy shifts planning focus:
  - From load to net-load
  - From peak demand and annual energy to hourly (8760) reliability under a variety of weather conditions

Moderate shares of VG increase the value of storage (broadly defined)

For example, solar and 4-hour storage work well together:



With storage peak demand period is now > 4 hours

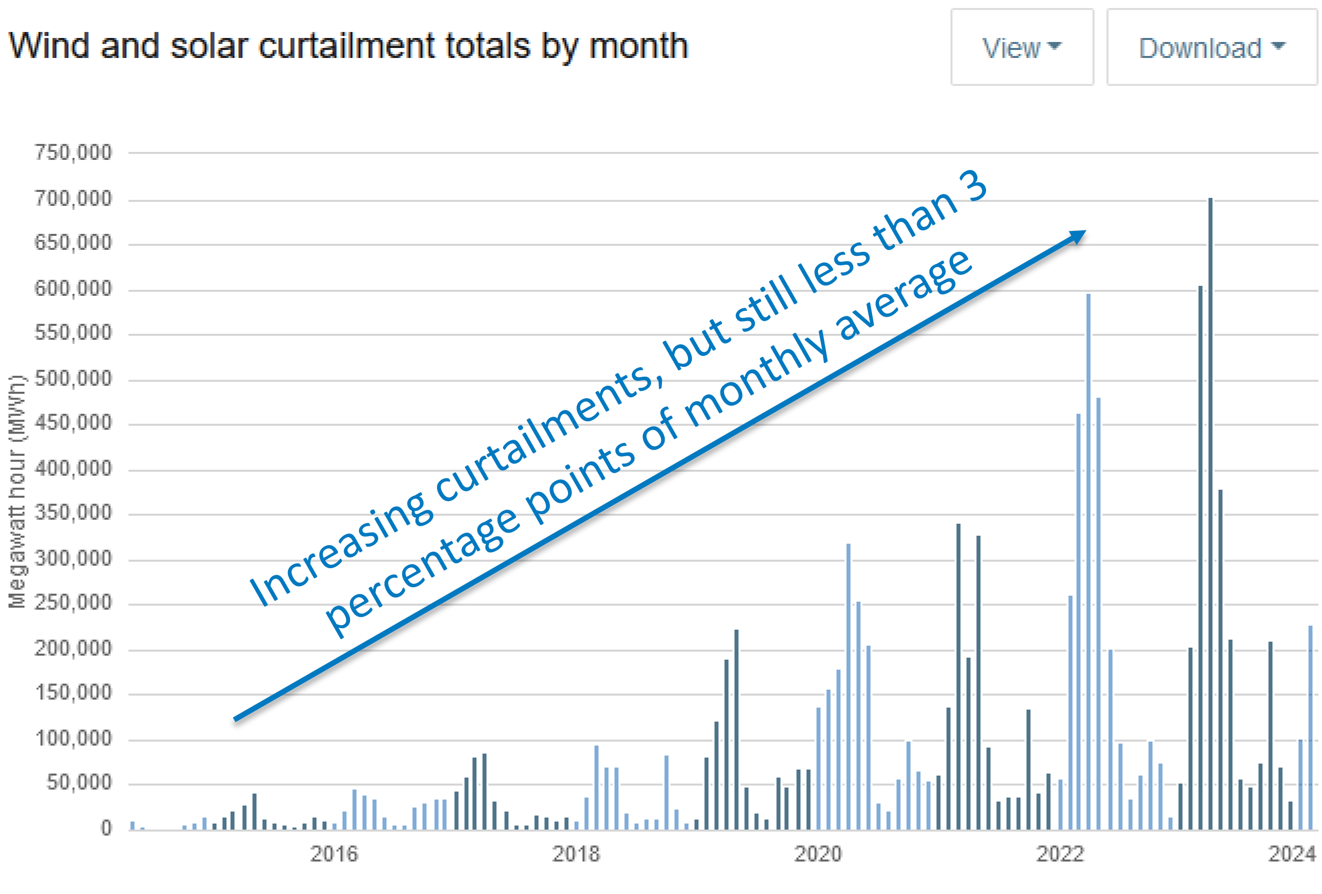


More PV narrows the net load peak

Source: Denholm et al. (2023)

Moderate shares of VG increase the value of storage (broadly defined)

For example, California Independent System Operator (CAISO) economic curtailments highlight advantageous times for charging storage:



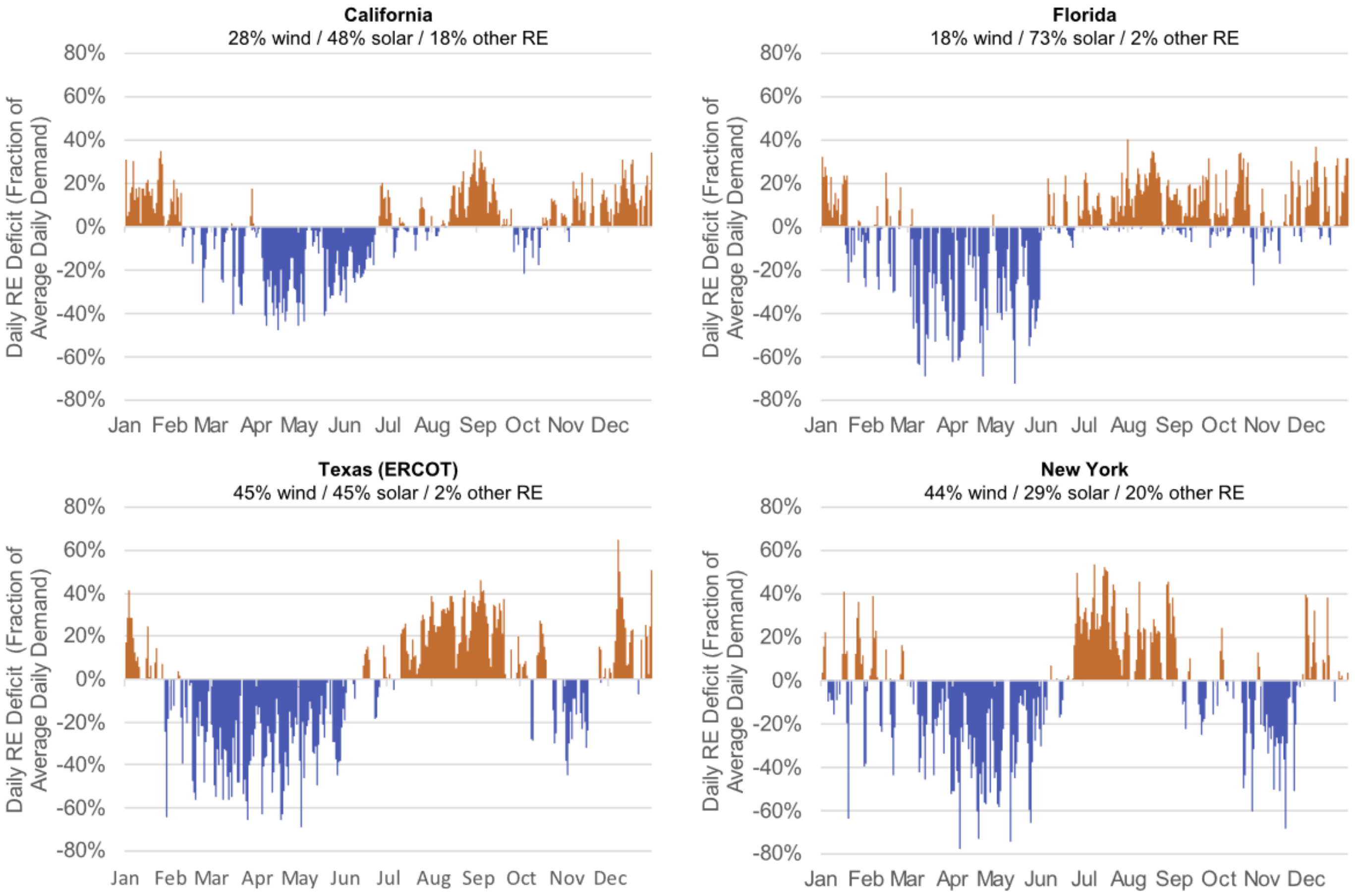
Source: http://www.caiso.com/informed/Pages/ManagingOversupply.aspx Updated as of 3/7/2024

Metric	2014	2015	2016	2017	2018	2019	2020	2021	2022
Load (Avg. Monthly TWh)	24.8	24.6	24.2	24.3	23.8	23.1	22.7	23.2	24.0
Solar Share (%)	4.2	6.0	8.1	10.2	11.4	12.3	13.2	14.2	17.0
Wind Share (%)	8.1	8.2	9.1	9.4	11.5	10.2	11.1	11.4	10.8

https://www.energy.ca.gov/data-reports/energy-almanac/california-electricity-data/2022-total-system-electric-generation

Deep decarbonization creates new reliability challenges

Grid Decarbonization → **Seasonal Mismatch**



Source: Mai et al. (2022)

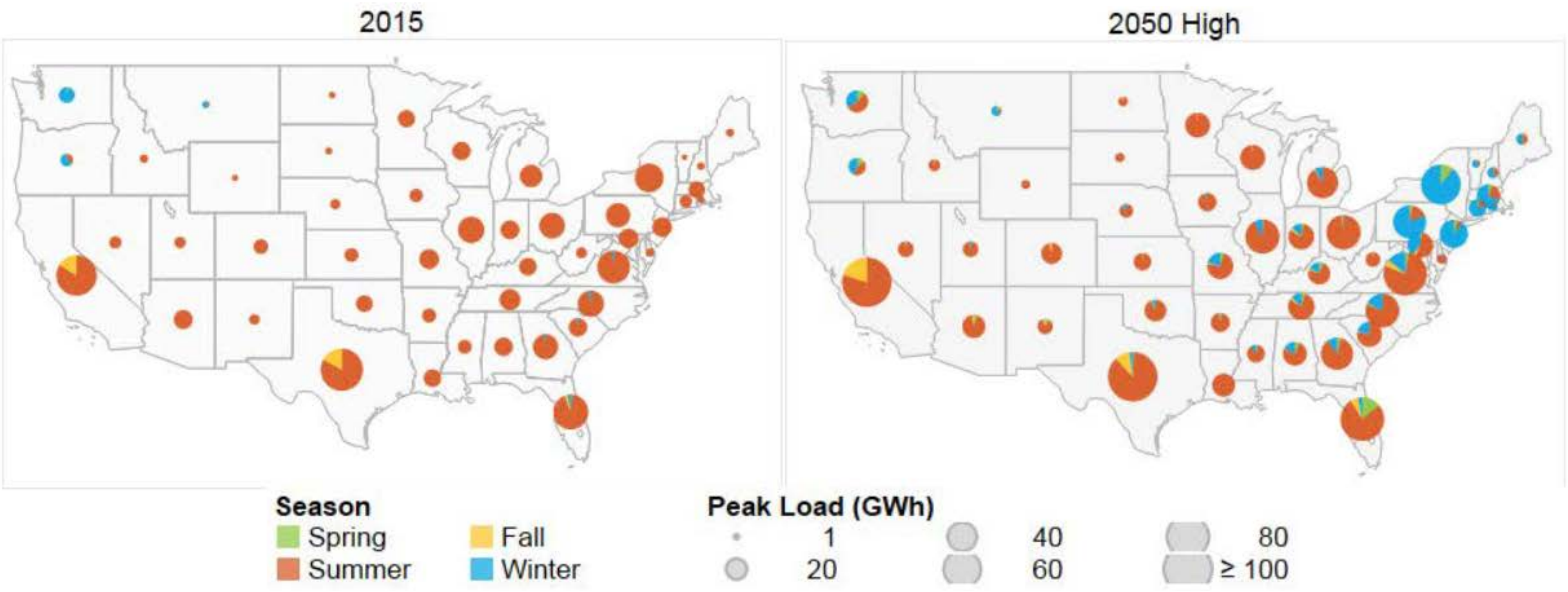
Although the particulars vary, all four of these locations show:

- Under-supply (orange) of renewable electricity during peak seasons (summer and winter)
- Over-supply (blue) of renewable electricity during shoulder seasons (spring and fall)

Depending on the balance-of-system (e.g., storages, thermal generators, etc.), these patterns can lead to multi-day energy droughts.

Deep decarbonization creates new reliability challenges

Demand Electrification → **Winter Peaking**



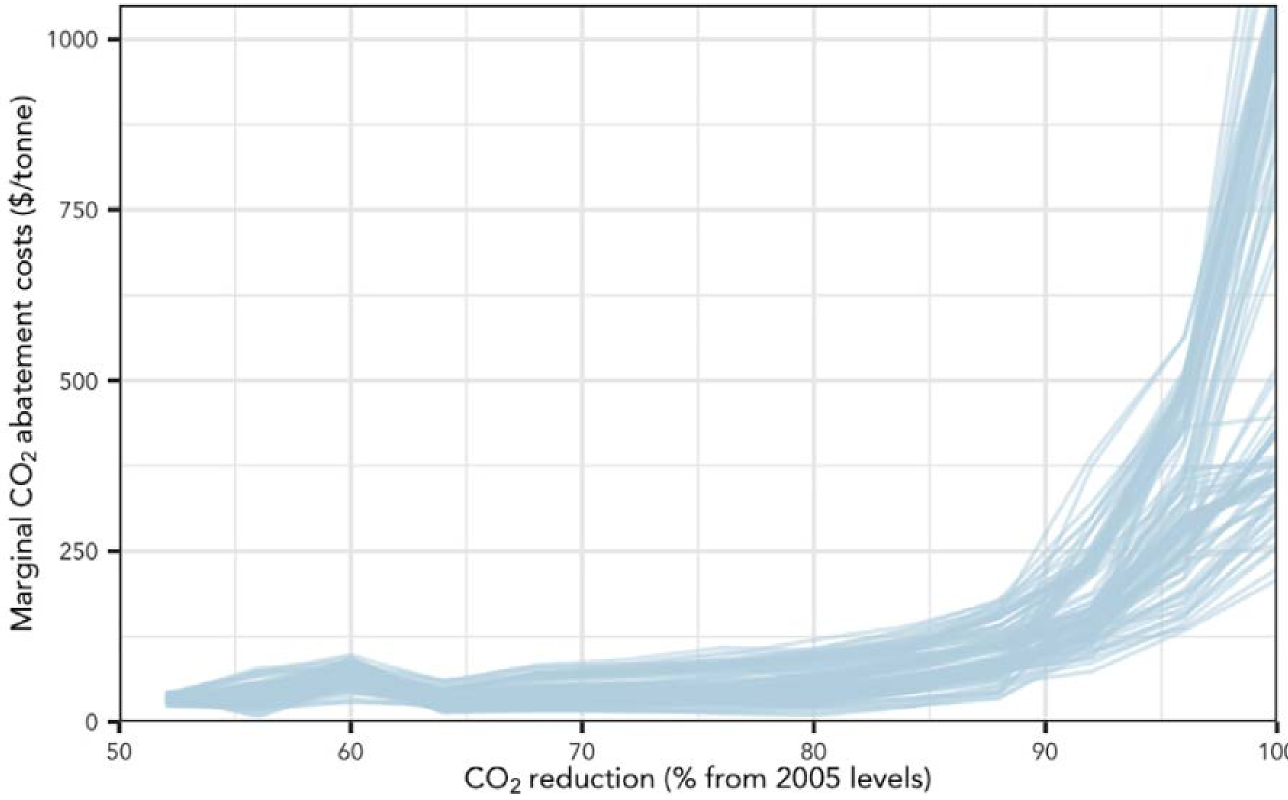
Total demand during the top hour (pie size) and seasonal distribution of the top 100 demand hours (pie wedge color) per state

Source: Mai et al. (2018)

- Building electrification shifts more top-100 hours to winter
- Winter peaking systems are challenging from a reliability perspective:
  - Less solar energy is available
  - Energy shortfalls are more consequential, because people are relying on electricity for heating

Abatement costs increase nonlinearly over the last 10% of power system decarbonization

CO_2 abatement costs estimated from U.S. power sector capacity expansion model simulations with technology cost, siting and technology availability, and demand growth sensitivities



Source: Mai et al. (2022)

- Depending on modeling assumptions, CO_2 reductions of 80-95% are possible for $100/metric ton CO_2 or less
- Abatement costs for the “last 10%” could be much higher, raising questions about when certain sectors and end-uses should electrify or otherwise decarbonize

Industry Decarbonization

Pillars of Industrial Decarbonization

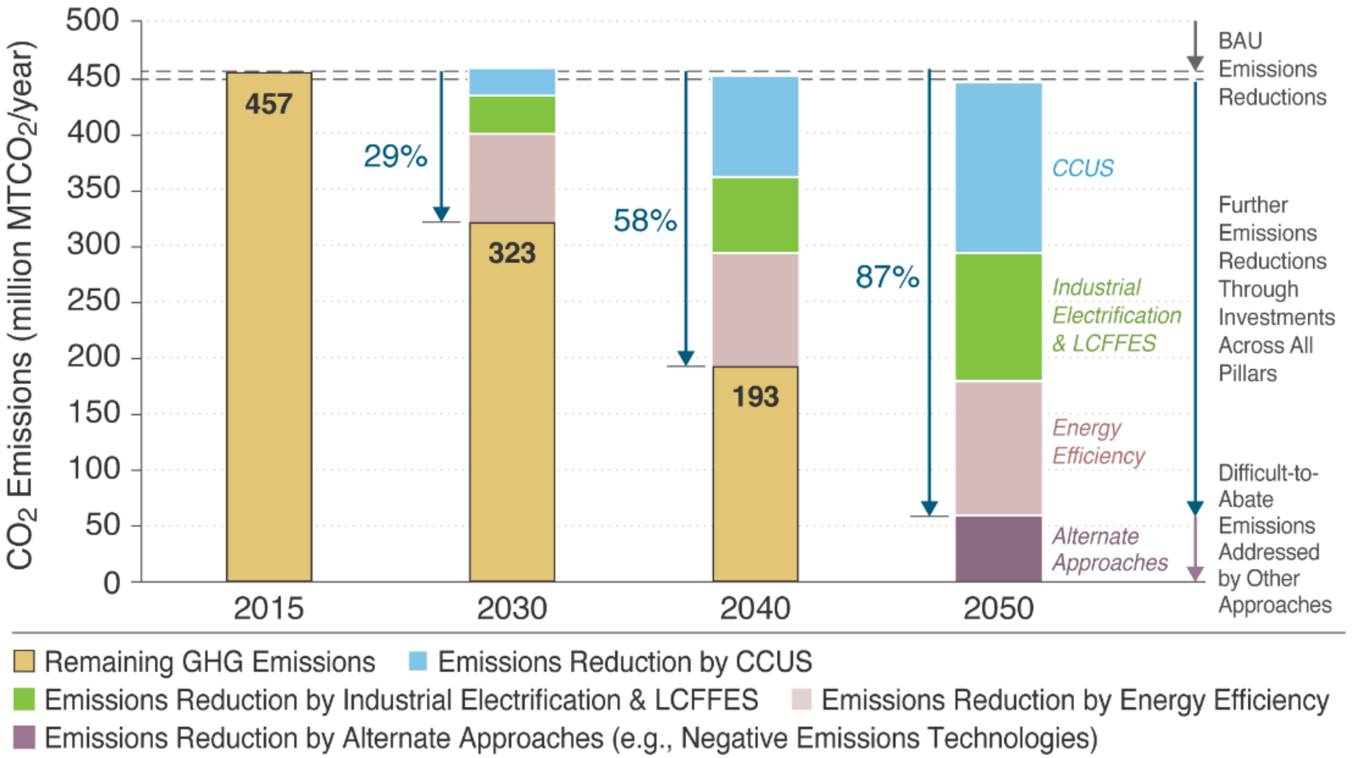
U.S. DOE Industrial Decarbonization Roadmap describes five pillars:

- Energy efficiency
- Industrial electrification
- Low-carbon fuels, feedstocks, and energy sources (LCFFES)
- Carbon capture, utilization, and storage (CCUS)
- Alternative approaches, including negative emissions technologies

that can be used to decarbonize five industrial sectors (Cresko et al. 2022)

TABLE ES 1. SCOPE OF EMISSIONS INCLUDED IN ROADMAP SCENARIO MODELING & ANALYSIS

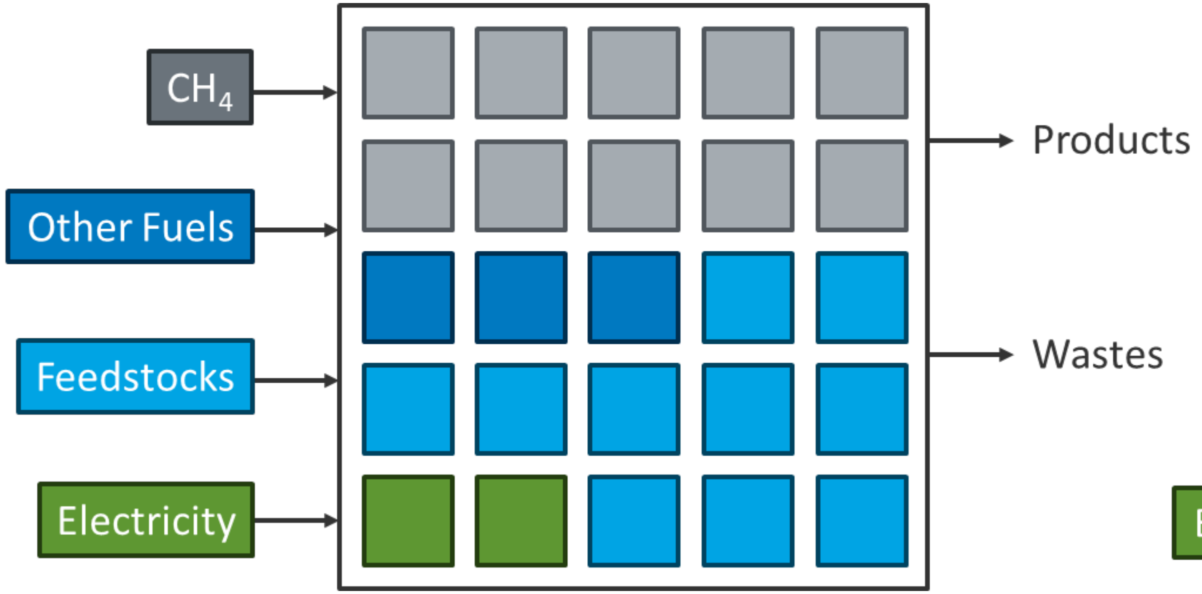
Industry Subsector	Electricity Generation CO_2 Emissions	Fuel-Related CO_2 Emissions	Process-Related CO_2 Emissions	CH_4, N_2O, and Other Non-CO_2 GHG Emissions	Subsector Coverage in Analysis
Iron and steel	Included	Included	Included*	Not included	Full subsector coverage
Chemicals	Included	Included	Not included	Not included	Partial coverage**
Food and beverage	Included	Included	N/A ***	Not included	Partial coverage**
Petroleum refining	Included	Included	N/A ***	Not included	Full subsector coverage
Cement	Included	Included	Included	Not included	Full subsector coverage

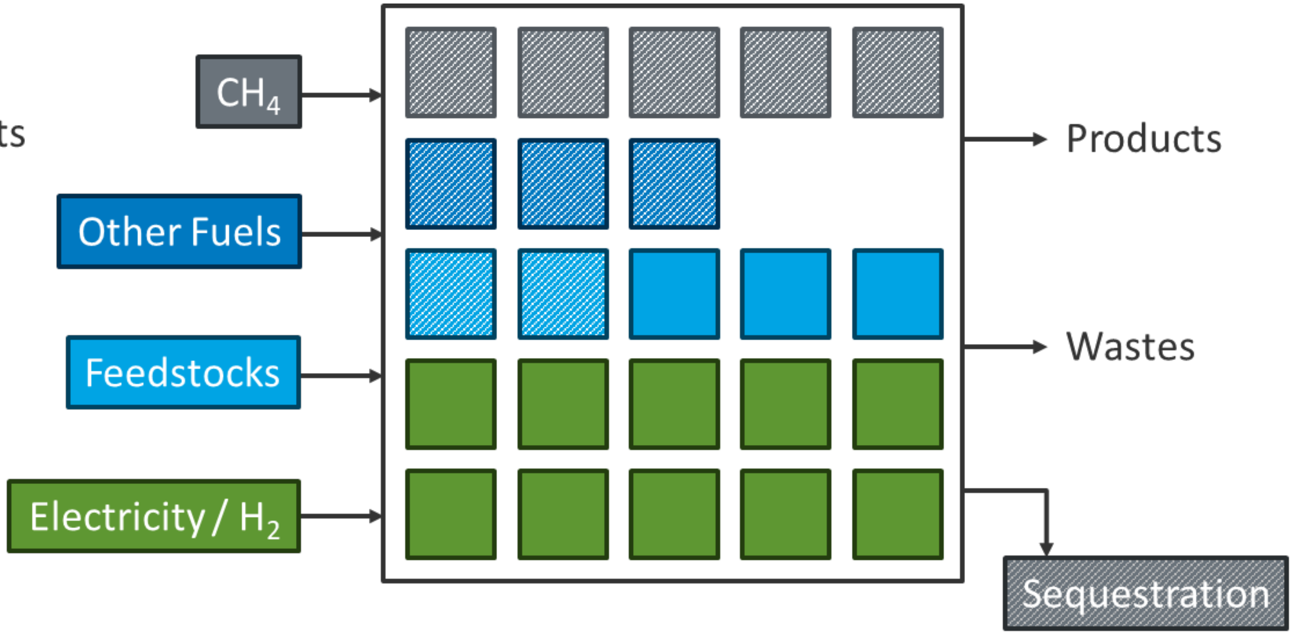


Old Paradigm

New Paradigm

Energy for Heat and Power and Embedded in Feedstocks





- Natural gas provides significant heat, power, and feedstock energy
- Other fuels and feedstocks are also major contributors
- Electricity has minor role
- Greenhouse gas (GHG) emissions are unmitigated

- Direct & indirect electrification has a major role
- CCUS is applied to many heat, power, and other chemical processes
- The ultimate mix of these technologies per sector and for industry as a whole is highly unknown

Proportions shown are loosely based on the Chemical Manufacturing data and decarbonization scenario in Cresko et al. (2022).

Industry-Grid Interactions

	Old Paradigm	New Paradigm
Planning	• Interruptible rates, in part to encourage economic development	• Decarbonization policy and incentives • Greenfield design vs. brownfield retrofit • Co-design with the grid / micro-grids • Co-design with multiple energy carrier networks (regional hubs?)
Operations	• Demand charge management • Infrequent calls for peak load reduction • More recently: – Increased auditing – More frequent calls – More types of peak load reduction	• Process scheduling / shifting via utilization of storage • On-site or regional electrolytic production of H_2, NH_3, other feedstocks • Increased wholesale market participation • Daily, weekly, monthly, seasonal co-optimization with electricity supply

Open Problems in Industry-Grid Interactions

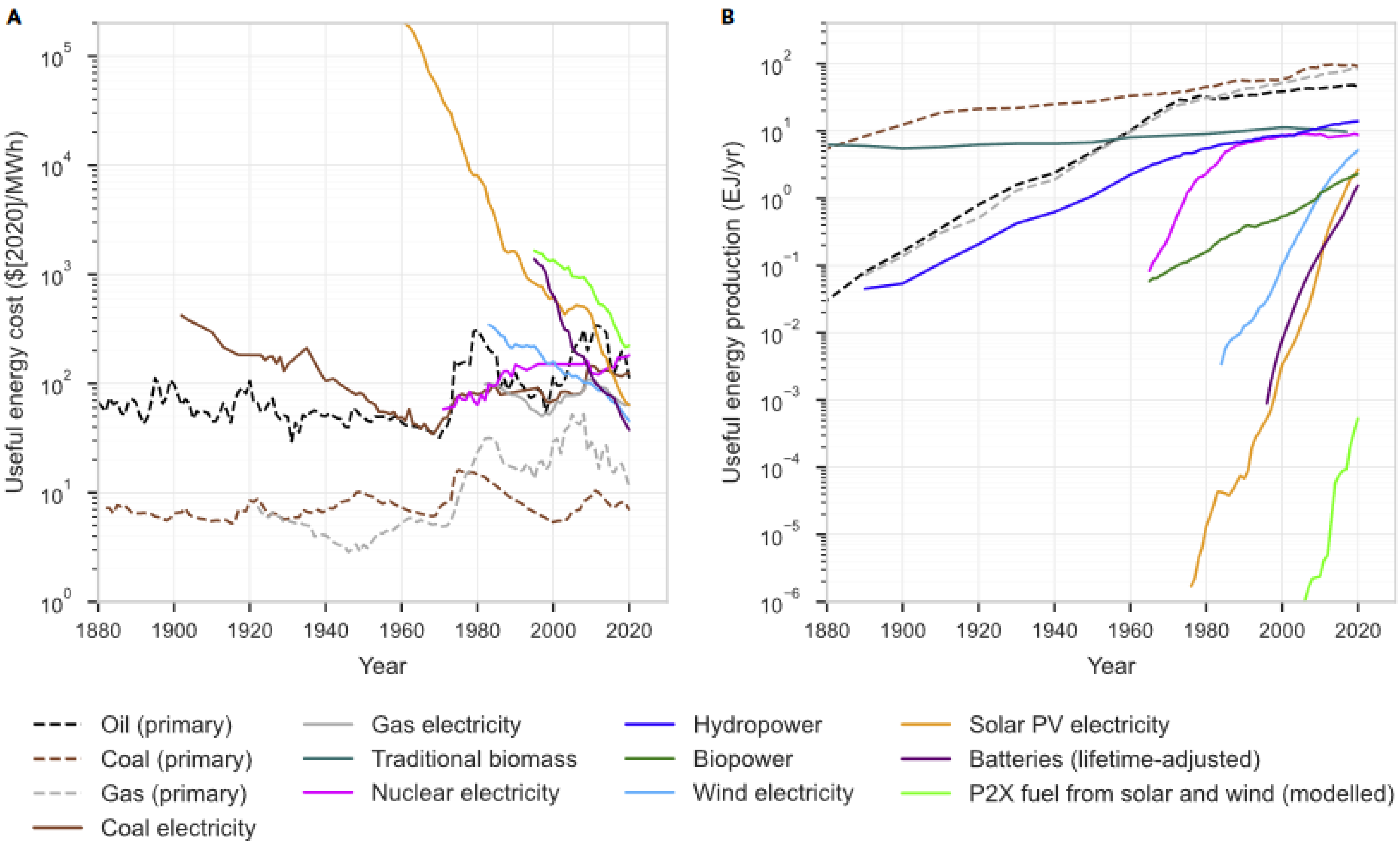
Planning Problems

Decarbonization Policy and Incentives

- R&D funding, deployment incentives, and decarbonization mandates can drive down costs through increased deployment
- The particulars influence what technologies become cost-competitive and when

Challenges

1. When is the right time to switch technologies / buy into a new technology?
2. Are all the technologies industry needs to decarbonize receiving R&D and other supports?



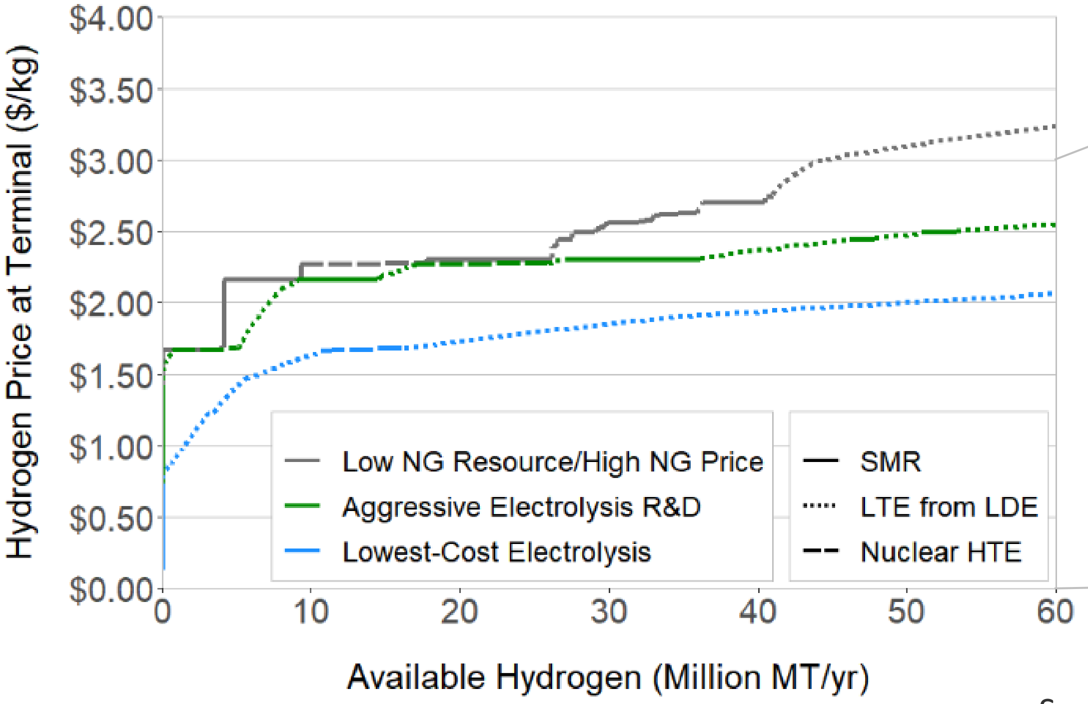
Source: Way et al. (2022); P2X fuel includes hydrogen, ammonia, methane, methanol, etc.

Decarbonization Policy and Incentives

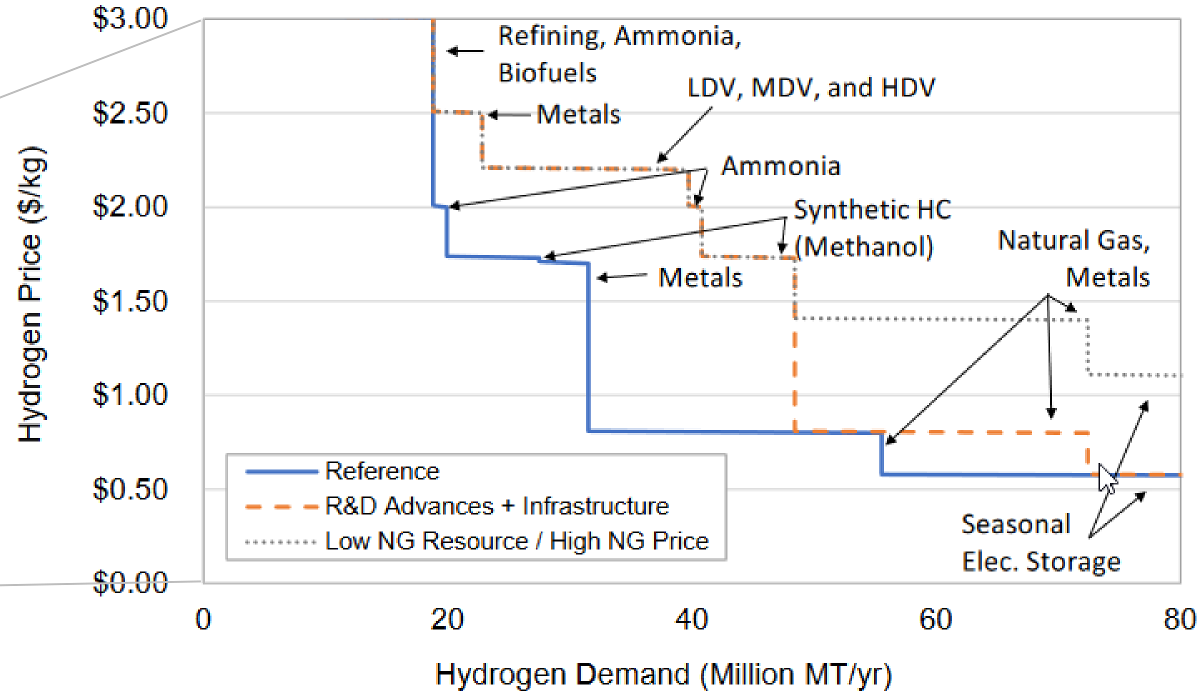
What's the Potential Scale of Electrolytic Production of H_2, NH_3, and Other Feedstocks?

Aggregated Supply Curves

(Reference case in backmatter)



Aggregated Demand Curves

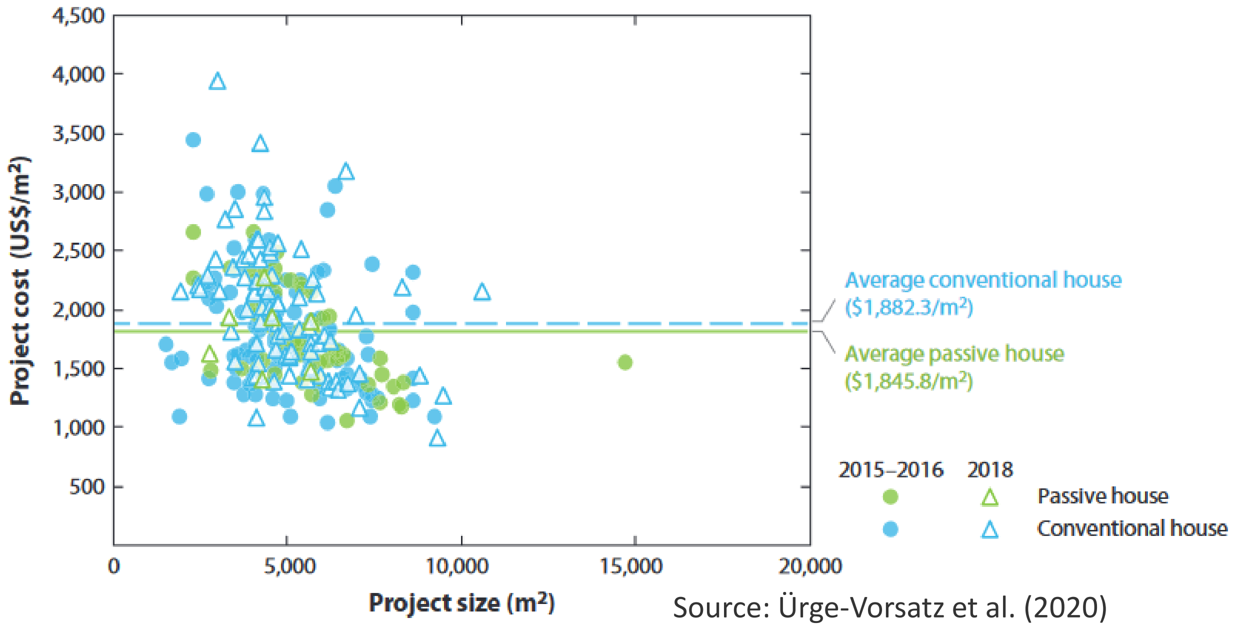


Source: Ruth et al. (2020)

- In the H2@Scale Study, low-temperature electrolysis for many end-uses only occurs for the "lowest-cost electrolysis" supply scenario combined with the "R&D Advances + Infrastructure" demand scenario

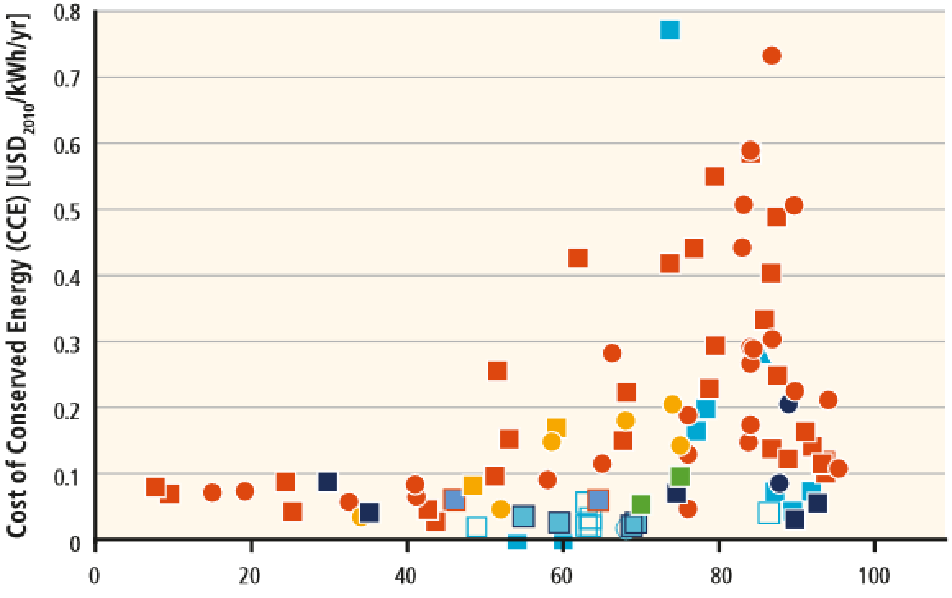
Greenfield Design vs. Brownfield Retrofit

Per floor area cost of housing projects funded by the Pennsylvania Housing Finance Authority (additional points awarded to certified Passive House projects starting in 2015)



Source: Ürge-Vorsatz et al. (2020)

Cost of energy saved in some European building retrofit case studies



Source: Lucon et al. (2014)

- High efficiency buildings can often be built (***new construction***) at or below conventional construction costs ***if they are designed to those standards up front.*** Retrofits to the same levels of energy efficiency tend to be more costly.
- We can expect similar findings for industrial facilities. Related to the grid,
  - Greenfield design means substation(s) and other electrical infrastructure can be sized properly to begin with
  - Brownfield retrofits with electrification means electrical upgrades throughout and/or new substation(s)
- Flexibility and controllability are examples of other greenfield vs. brownfield considerations

Co-design with the Grid / Microgrids

Why co-design?

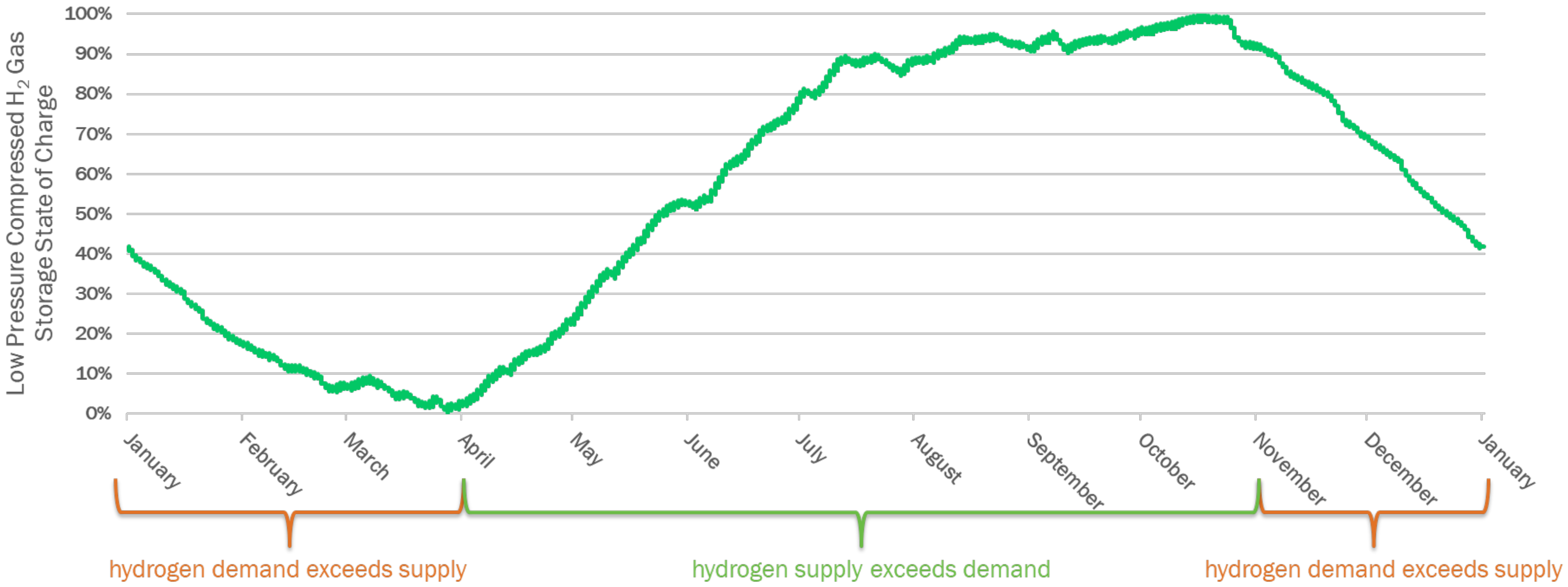
- Energy supply expected to be variable and uncertain
- Reduce energy, fuel, and feedstock costs and cost variability, especially if some inputs are produced electrolytically on-site
- Increase plant reliability
- Align reliability event plans with the grid / utilities and surrounding communities

Some considerations

- Energy and product storage
- Design for flexibility, maybe co-design controls
- How many modes of operation are there?

Hydrogen Storage Sizing Example

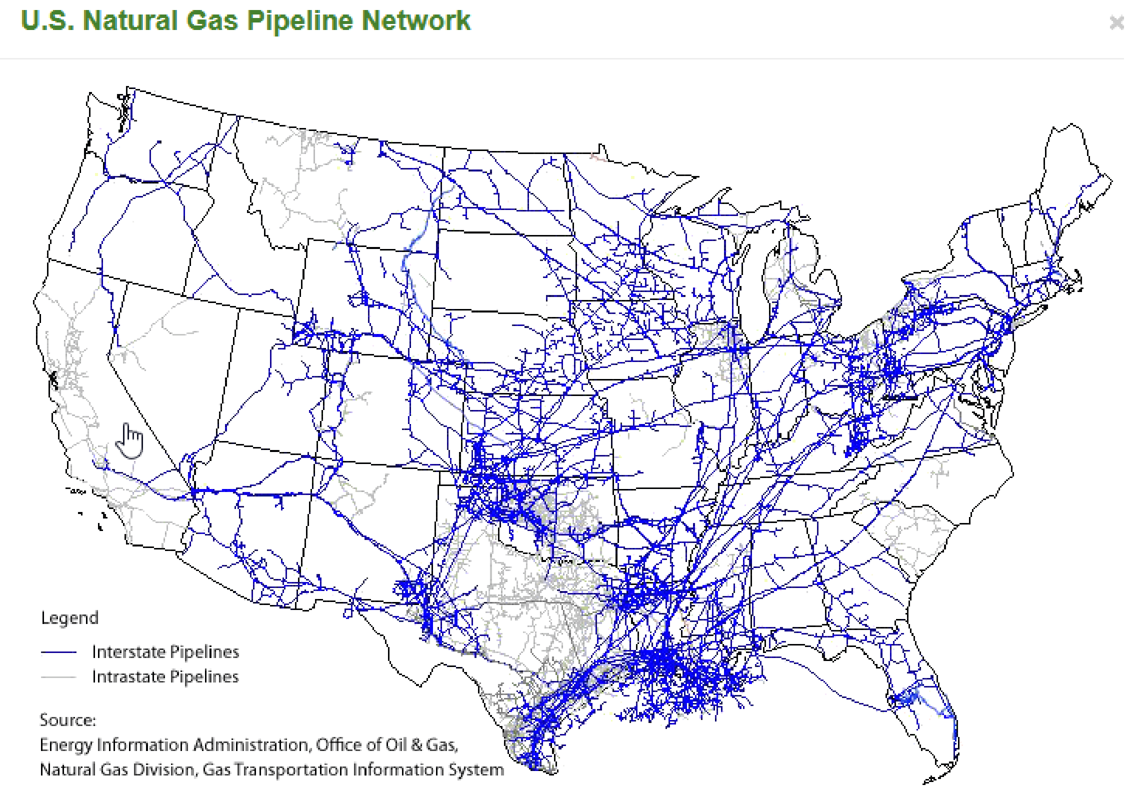
Off-grid solar generating hydrogen for heavy-duty vehicle fueling application



Source: Topolski et al. (2023)

- Above is a simple example that illustrates buffering seasonal energy supply with a large storage (in this case, hydrogen)
- Co-designed industrial facilities might build in both daily and seasonal storage

Co-design with Multiple Networks



Accessed via: https://afdc.energy.gov/fuels/natural-gas-distribution

Example of Optimized CO_2 Capture and Storage Network

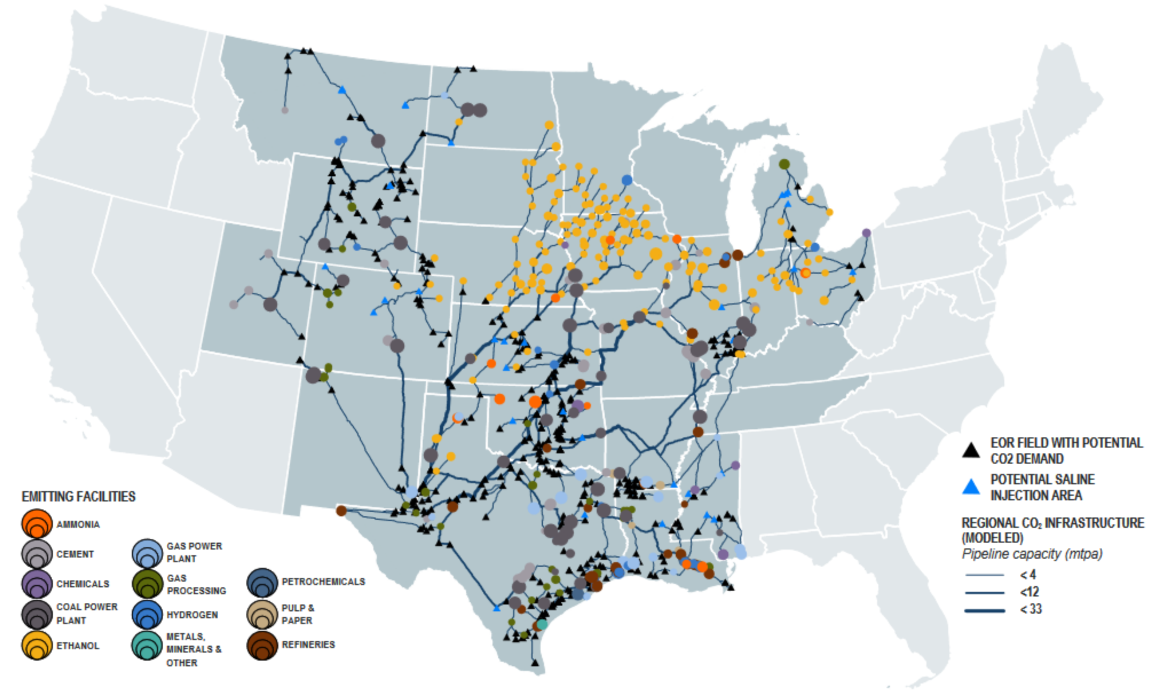


Figure authored by GPI based on results from the SimCCS model.

- Currently, industry is supplied by: electricity grid, oil & gas pipelines, water infrastructure, local transport of various inputs and waste products (e.g., steam, N_2, O_2, Cl_2, etc.)
- Future industry might want pipeline transport of CO_2, H_2, etc.; Current pipelines could be repurposed or retired.
- Co-design of networks and storages, inclusive of new investments, retrofits, and retirements, at the site, local, regional, and national scales could reduce transition costs

Operational Problems

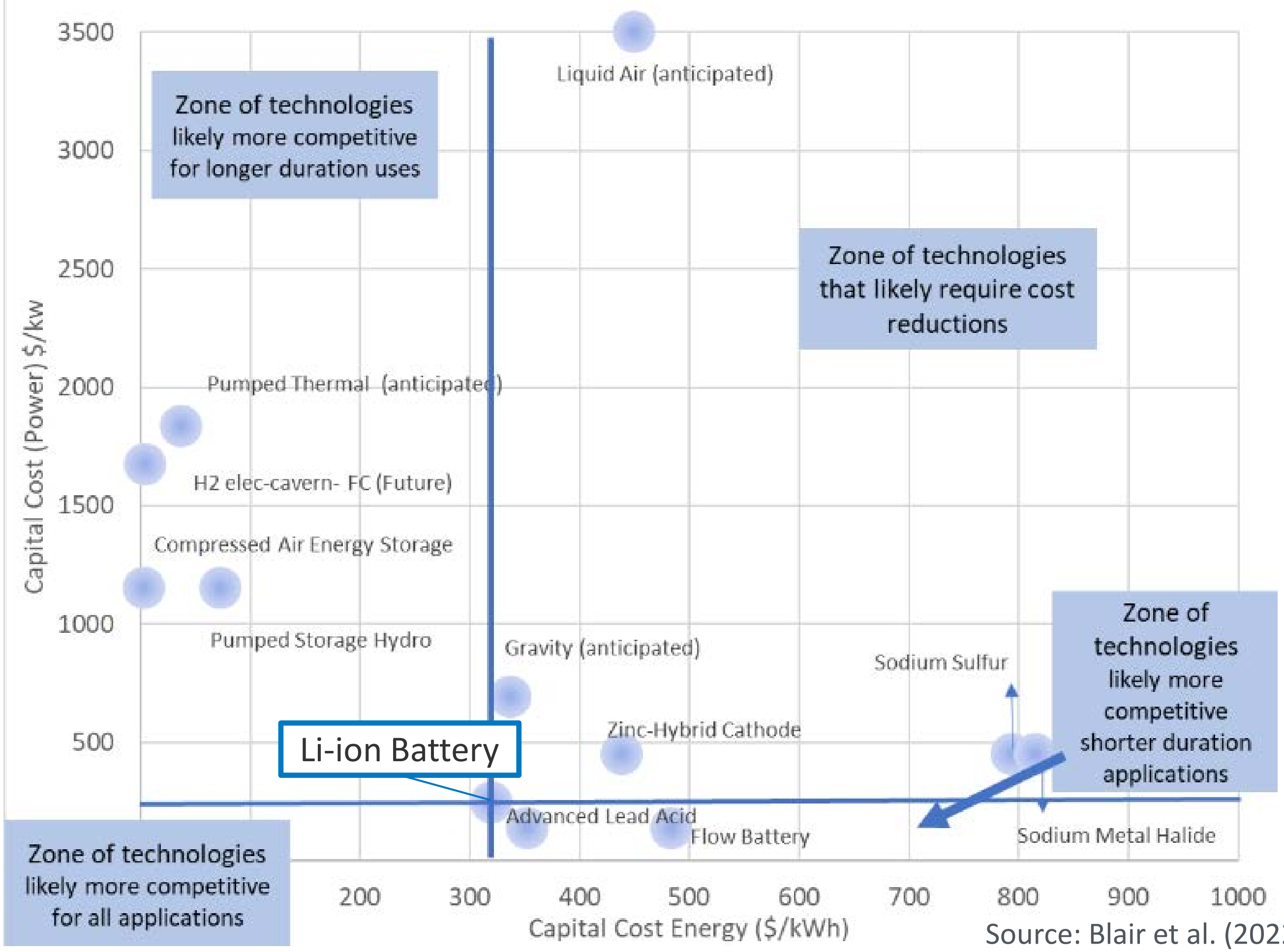
Process Scheduling / Shifting via Utilization of Storage

Value proposition

- Are there on-site storages / reservoirs of energy, feedstocks, intermediates, products, etc.?
- Can those storages and the processes connected to them be operated flexibly enough to shift load more cost-effectively than can utility-scale energy storage?

Operational considerations

- Are storage levels continuously measured?
- Are storage levels tracked in facility planning / operational / supervisory control software?
- Are controllability, stability, and safety bounds of flexible process operations well known?
- Can storage levels be combined with production schedules to produce hourly, daily, and weekly bounds on electricity consumption?

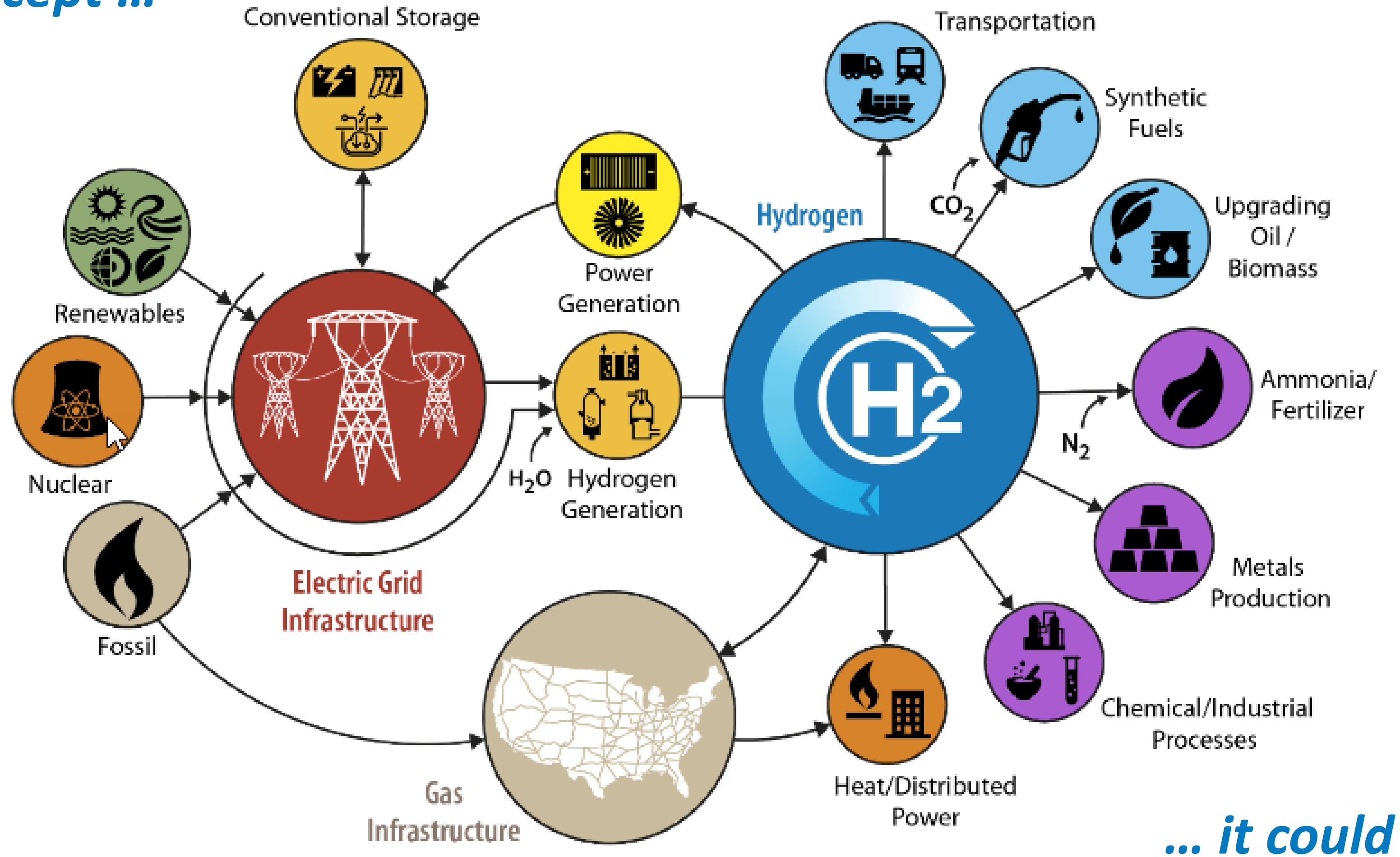


Source: Blair et al. (2022)

Comparing to utility-scale storage costs like those shown above requires determining capital and operational costs of industrial storage, and choosing a use case (charge/discharge pattern) as a basis for comparison

On-site or Regional Electrolytic Production of H_2, NH_3, and Other Feedstocks

H2@Scale Concept …



… it could be very complicated

Source: Ruth et al. (2020)

Increased Wholesale Market Participation

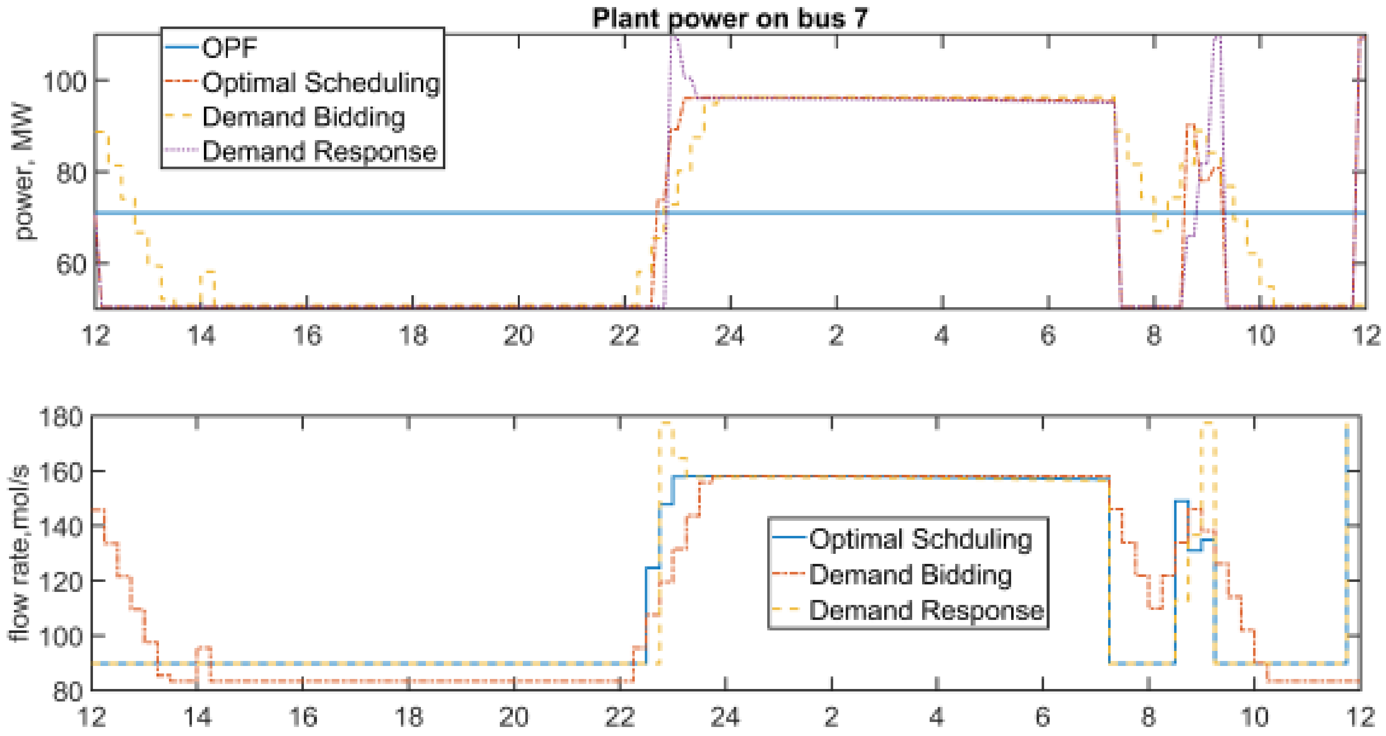
Why wholesale market participation?

- Improved reliability and price formation in systems with high shares of low-to-zero marginal cost resources
- Many customers self-scheduling to prices can increase system costs by violating the price-taking assumption

Participation model considerations

- Must fit into a MW-scale Mixed Integer Linear Programming (MIP) formulation
- Energy constraints, e.g., to meet daily product demand, to manage storage state of charge
- Demand-side participation or the equivalent eliminates baselines and pay-for-curtailment

Chlor-alkali Plant Example



Source: Tang et al. (2024)

Near-co-optimal results can be achieved with limited information exchange (i.e., demand bidding compares favorably to optimal scheduling)

- **Demand bidding:** Linear model of plant power bounds, ramp rate limits and daily energy requirements, co-optimized with supply-side generators
- **Optimal scheduling:** Co-optimization of supply-side generators and full model of plant dynamics
- **Demand response:** Minimize energy costs per a fixed price profile

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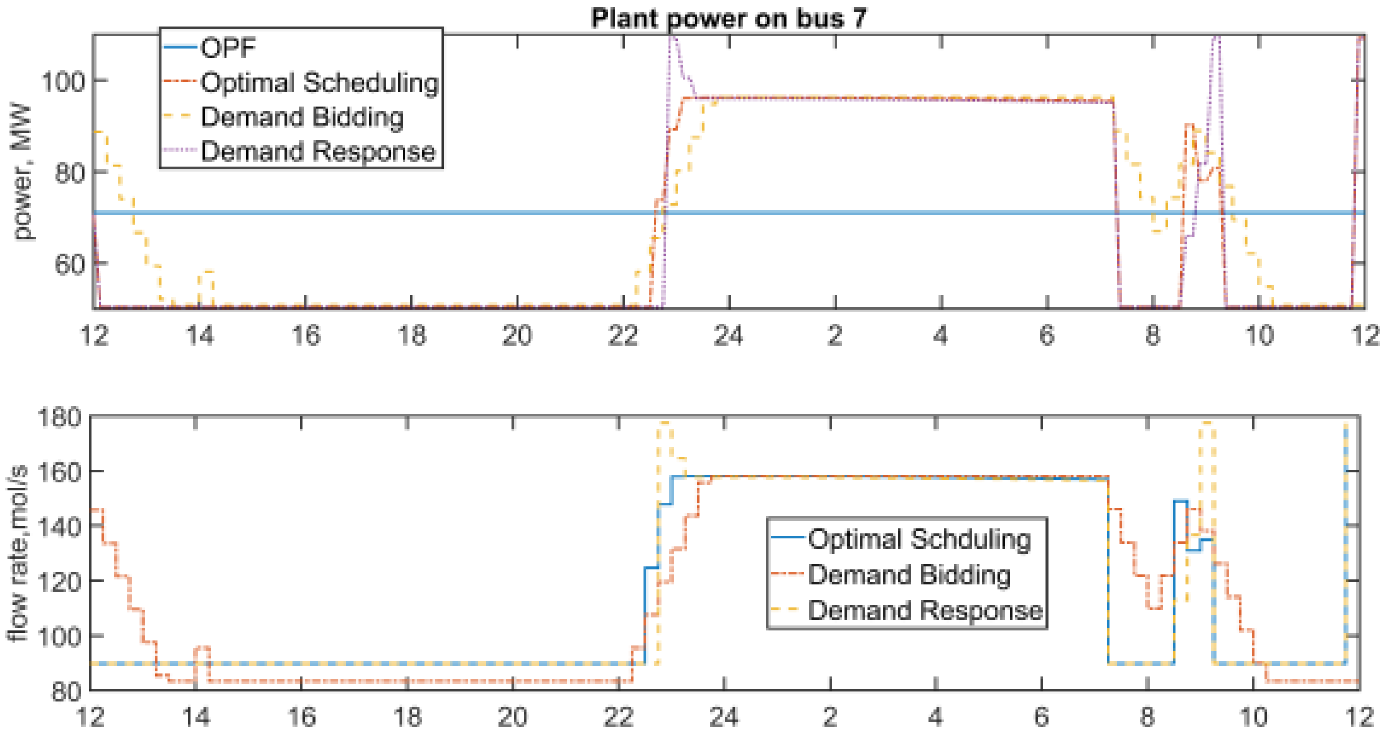
Participation considerations

- Metering and telemetry
- Site-level, automated knowledge of
  - Value of electricity consumption
  - Cost of on-site generation
  - Storage reservoir locations and states of charge
  - Operating constraints of processes, generators, and storages
- Ability to receive and respond to dispatch signals
  - Automated control capabilities
  - Robust knowledge of safe operating limits

Chlor-alkali Plant Example



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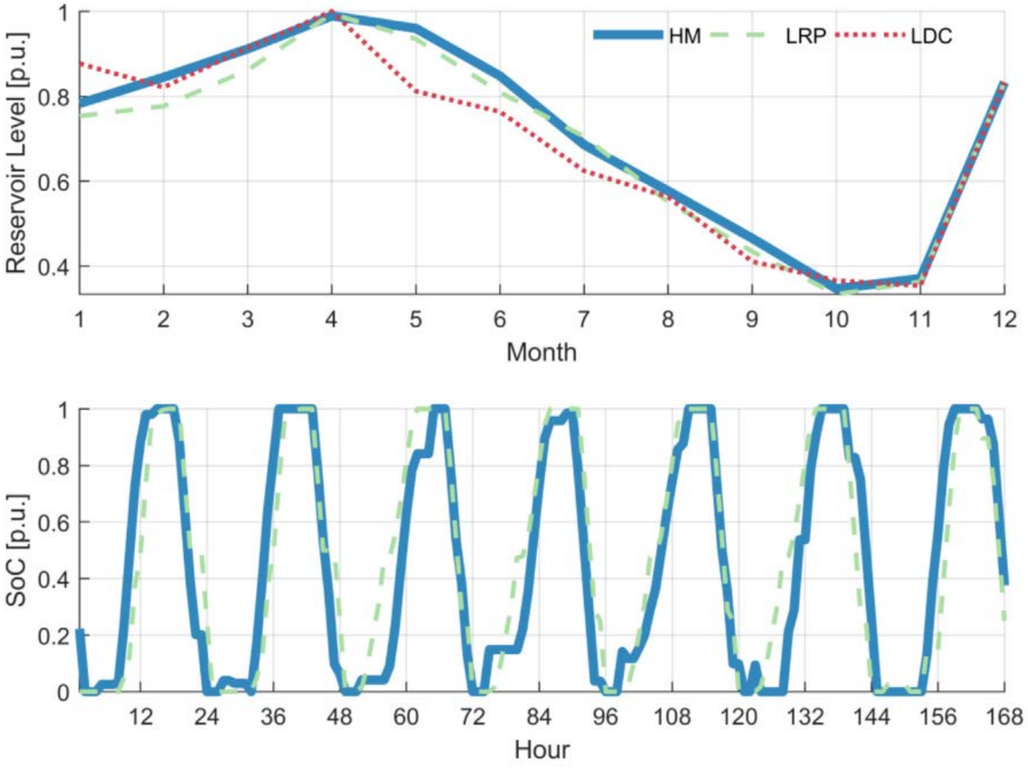
Daily, Weekly, Monthly, and Seasonal Co-optimization with Electricity Supply

	Grid	Industry
Season	• Large hydroelectric reservoirs • Planned maintenance • *Other long duration energy storage (e.g., H_2)* • *Advisory schedules based on climate patterns and net-load forecasts* • *Update and communicate resiliency plans*	• Planned maintenance • Some production schedules & workforce • Long duration storage of feedstocks, products • *Other long duration storage (e.g., energy carriers, other feedstocks, heat, intermediates)* • *Create and communicate net-load forecast* • *Update and communicate resiliency plans, impact of different system conditions on net-load*
Week	• Start-up/shut-down of large (e.g., coal) generators • Advisory schedules based on weather forecast • *Week-ahead wholesale markets including state-of-charge management for storages and temporally flexible loads*	• Detailed labor schedules • Some production schedules & inventory • *Bid for week ahead electricity consumption, including value of consumption and temporal flexibility*
Day	• Generators, storage, and demand resource dispatch • *Grid optimization of storage state-of-charge* • *Full-featured demand participation model, e.g., bid-to-buy, energy constraints to ensure product delivery, operational constraints, multiple configurations with transition costs*	• Final production schedules • Standard operating procedures • Automated controls • *Bid for day-ahead and real-time electricity consumption*

Existing *New* *Co-optimization*

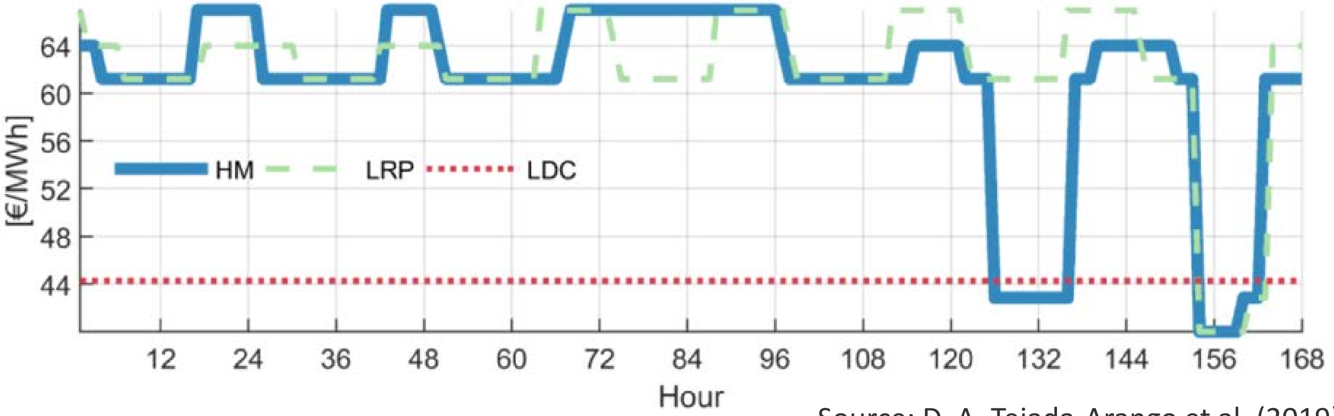
Daily, Weekly, Monthly, and Seasonal Co-optimization with Electricity Supply

Large hydropower and batteries provide storage at different timescales



Source: D. A. Tejada-Arango et al. (2019)

Storage value / opportunity cost computed using the Linked Representative Periods (LRP) model is an approximation compared to the Hourly Model (HM)



Source: D. A. Tejada-Arango et al. (2019)

- Storage and flexible demand participation models for wholesale electricity markets could be designed to manage state-of-charge using opportunity costs derived from longer-term scheduling (or other forward market positions) to inform shorter-term dispatch decisions (i.e., is the short-term value more or less than the expected long-term value for the next period)
- Such reforms, combined with the introduction of longer-term wholesale electricity markets could improve scheduling for industry and the grid

Conclusions

Common Themes

- **Plant-level supervisory data and scheduling:** Track value of electricity consumption, storage levels, plant state; Dispatch to meet product demand subject to external (e.g., grid) signals and operational constraints.
- **Coordination with the grid at planning and operational scales:** Right-size electrical and storage components of decarbonized processes; Design and operate in harmony with seasonal and diurnal patterns; Communicate limited information to grid operators to enable co-optimization of supply & demand; Perform scheduled maintenance during low energy times.
- **Design and coordination of on-site and networked energy, feedstock, and waste streams:** On-site electricity generation and conversion to other energy carriers (e.g., hydrogen) and/or feedstocks can increase plant resiliency; Participation in regional pipeline networks can increase economies of scale, enable use of multiple decarbonized energy and feedstock sources, enable CCUS.

Thank you

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This work was authored in part by the National Renewable Energy Laboratory, operated by Alliance for Sustainable Energy, LLC, for the U.S. Department of Energy (DOE) under Contract No. DE-AC36-08GO28308. Funding provided by DOE's Office of Energy Efficiency and Renewable Energy – Integrated Strategies Office, Strategic Analysis team and DOE's Advanced Research Projects Agency-Energy. The views expressed in the article do not necessarily represent the views of the DOE or the U.S. Government. The U.S. Government retains and the publisher, by accepting the article for publication, acknowledges that the U.S. Government retains a nonexclusive, paid-up, irrevocable, worldwide license to publish or reproduce the published form of this work, or allow others to do so, for U.S. Government purposes.

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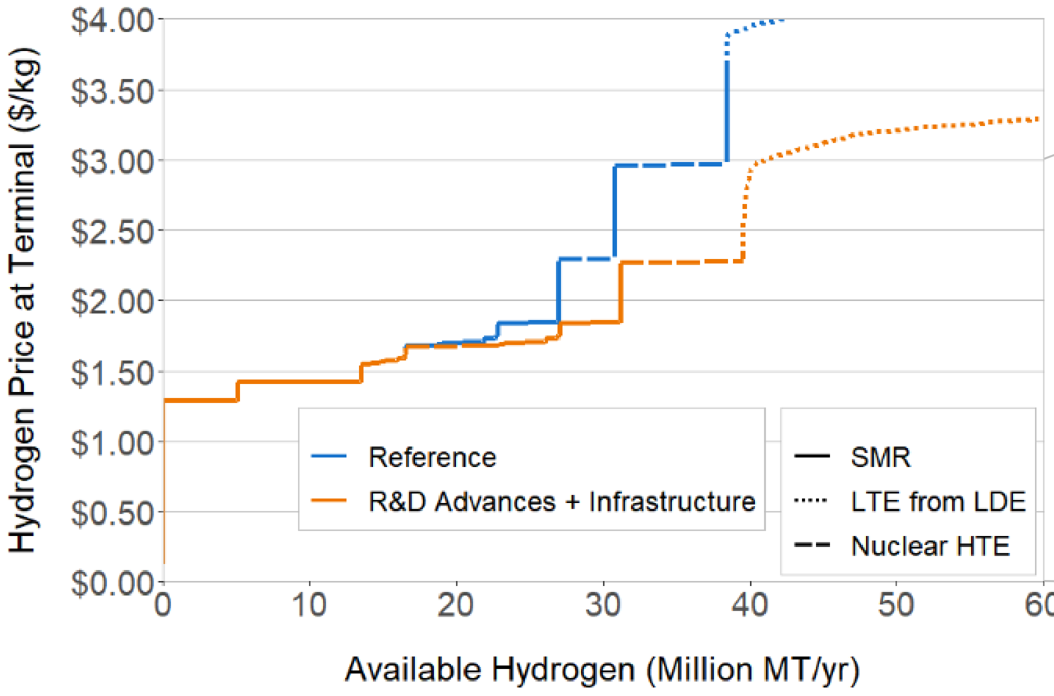
Backmatter

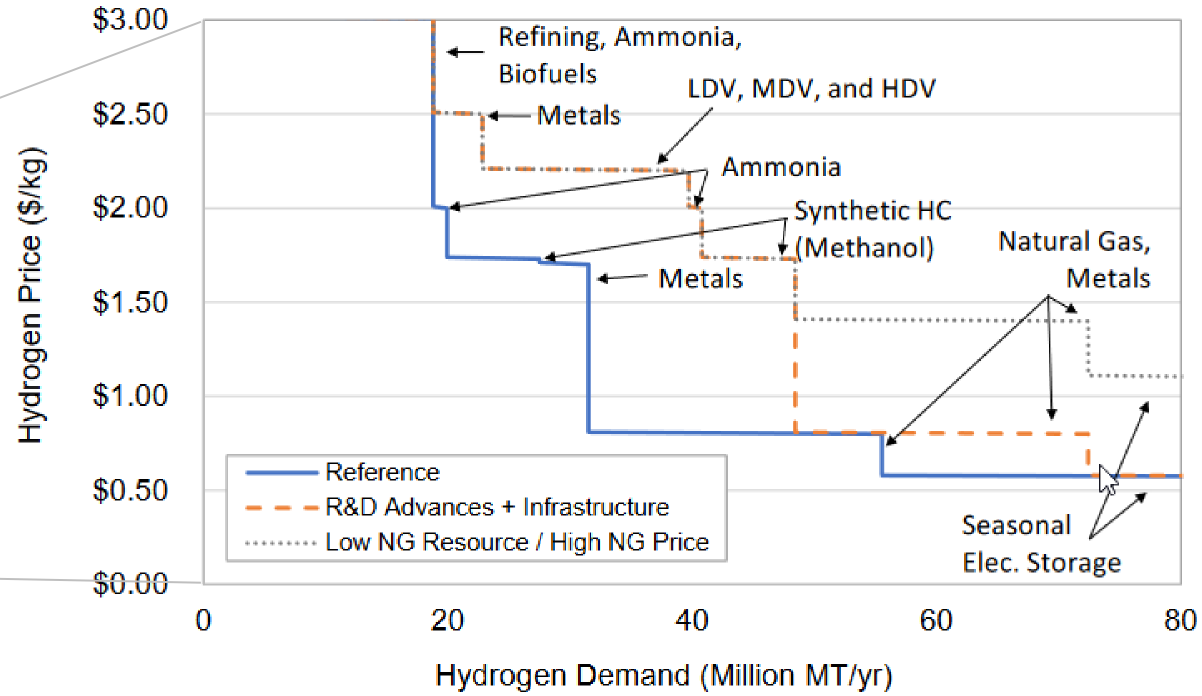
Decarbonization Policy and Incentives

What's the Potential Scale of Electrolytic Production of H_2, NH_3, and Other Feedstocks?

Aggregated Supply Curves



Aggregated Demand Curves



Source: Ruth et al. (2020)