Ammonia: Opportunities for Grid Support

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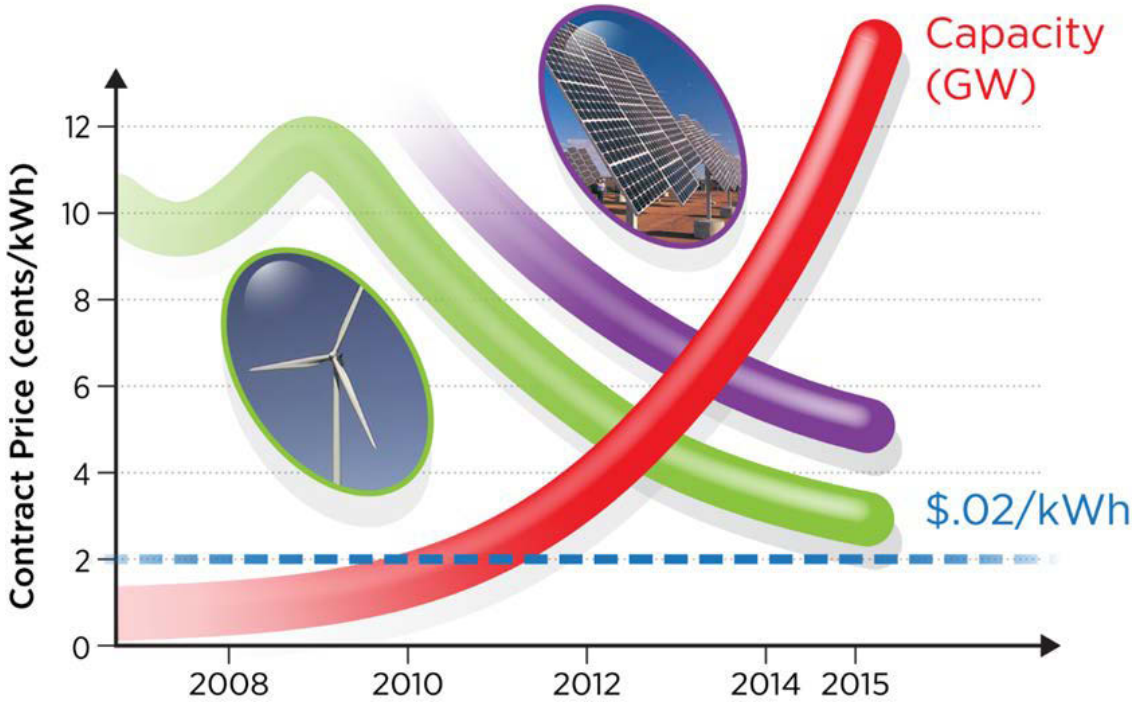
Technology Development is Impacting the Grid

- Cost of renewable electrons dropping dramatically
- Increased electrification
- Connectivity, autonomy, machine learning



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

Low Prices for Wind and Solar

Overall Summary and Pricing Received

	Technology	# of Bids	Bid MW (ICAP)	# of Projects	Project MW	Average Bid Price	Pricing Units	Comments
Asset Sale or Option	Combine Cycle Gas (CCGT)	7	4,846	4	3,055	$959.61	$/kW	
	Combustion Turbine (CT)	1						
	Solar	9	1,374	5	669	$1,151.01	$/kW	
	Wind	8	1,807	7	1,607	$1,457.07	$/kW	
	Solar + Storage	4	705	3	465	$1,182.79	$/kW	
	Wind + Solar + Storage	1						
	Storage	1						
Purchase Power Agreement	Combine Cycle Gas (CCGT)	8	2,715	6	2,415	$7.86	$/kW-Mo	+ fuel and variable O&M
	Solar + Storage	7	1,055	5	755	$5.90	$/kW-Mo	+ $35/MWh (Average)
	Storage	8	1,055	5	925	$11.24	$/kW-Mo	
	Solar	26	3,591	16	1,911	$35.67	$/MWh	
	Wind	6	788	4	603	$26.97	$/MWh	
	Fossil	3	1,494	2	772	N/A		Structure not amenable to price comparison
	Demand Response	1						
	Total	**90**	**20,585**	**59**	**13,247**			

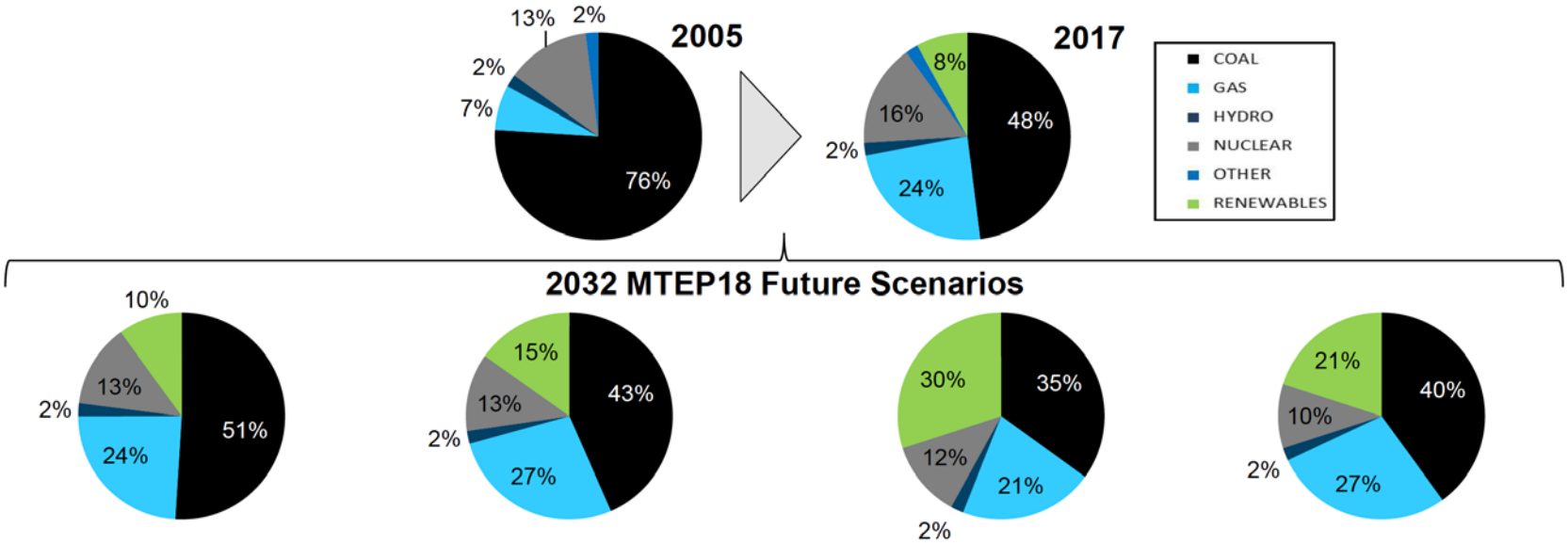
Indiana NIPSCO IRP Pricing

- Wind and solar power purchase agreements (PPAs) are key opportunities.
- Indiana IRP Averages:
  - Wind <$27/MWh
  - Solar <$36/MWh
- Expiring PPAs may have even lower prices

Source https://pv-magazine-usa.com/2018/07/24/indiana-solar-solarstorage-solarwindstorage-oh-my/ (July 24, 2018)

Impacting Grid Mixes around the World

The Midwest Independent System Operator (MISO) expects significant growth in renewable and gas-fired generation



Limited Fleet Change
Stalled generation fleet changes. Limited renewables additions driven solely by existing RPS under limited demand growth.

Continued Fleet Change
Continuation of the renewable addition and coal retirement trends of the past decade.

Accelerated Fleet Change
Renewables and demand side technologies added at a rate above historical trends. Fleet changes result in a 20% CO_2 emission reduction[1].

Distributed & Emerging Tech
New renewable additions largely distributed and storage resources co-located with largest sites.

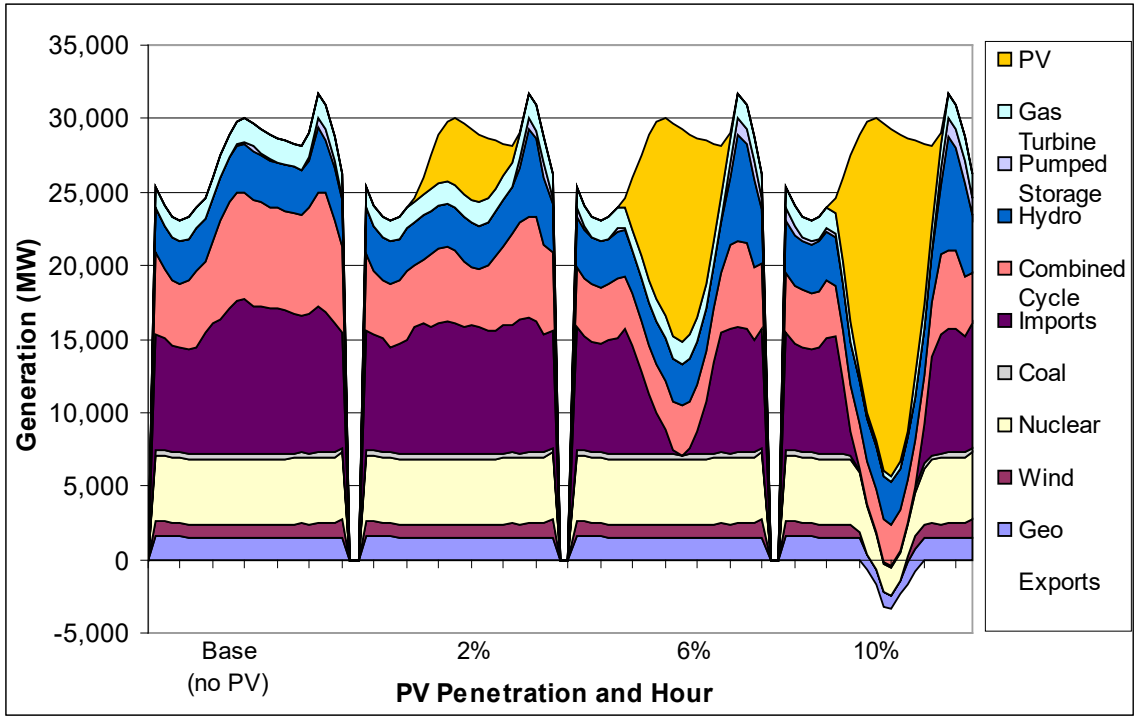
Source: Bakke, et al "Evolution of the Grid in the MISO region" (Nov 7, 2017)

Need for Additional Grid Flexibility

Increased renewables penetration can lead to

1) over generation / curtailment

2) unprecedented ramp rates for dispatchable generation

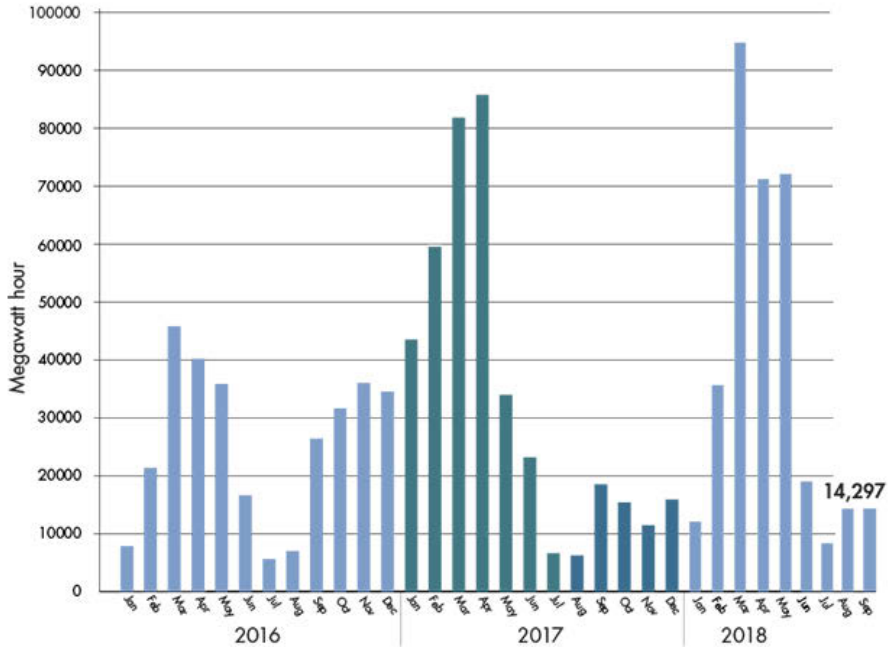


Denholm, P.; Margolis, R.M.; Milford, J. "Production Cost Modeling for High Levels of Photovoltaics Penetration." NREL/TP-581-42305. Golden, CO: National Renewable Energy Laboratory. https://www.nrel.gov/docs/fy08osti/42305.pdf (February 2008)

Curtailment in California

- During January – July 2018, California curtailed over 315,000 MWh
- If California meets its 50% Renewable Portfolio Standard target, up to 5% of the renewable electricity generated could be curtailed

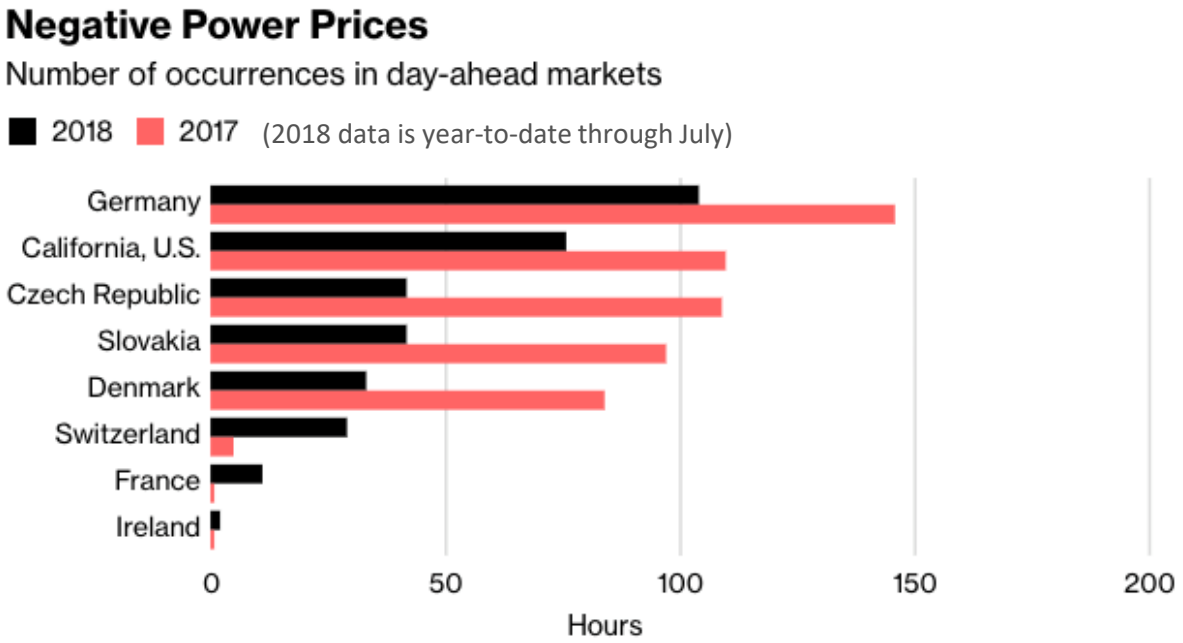
Monthly Curtailment in California



Sources: CAISO Data from http://www.caiso.com/informed/Pages/ManagingOversupply.aspx. Accessed October 15, 2018 James Nelson & Laura Wisland. Achieving 50 Percent Renewable Energy in California. https://www.ucsusa.org/sites/default/files/attach/2015/08/Achieving-50-Percent-Renewable-Electricity-In-California.pdf (August 2015)

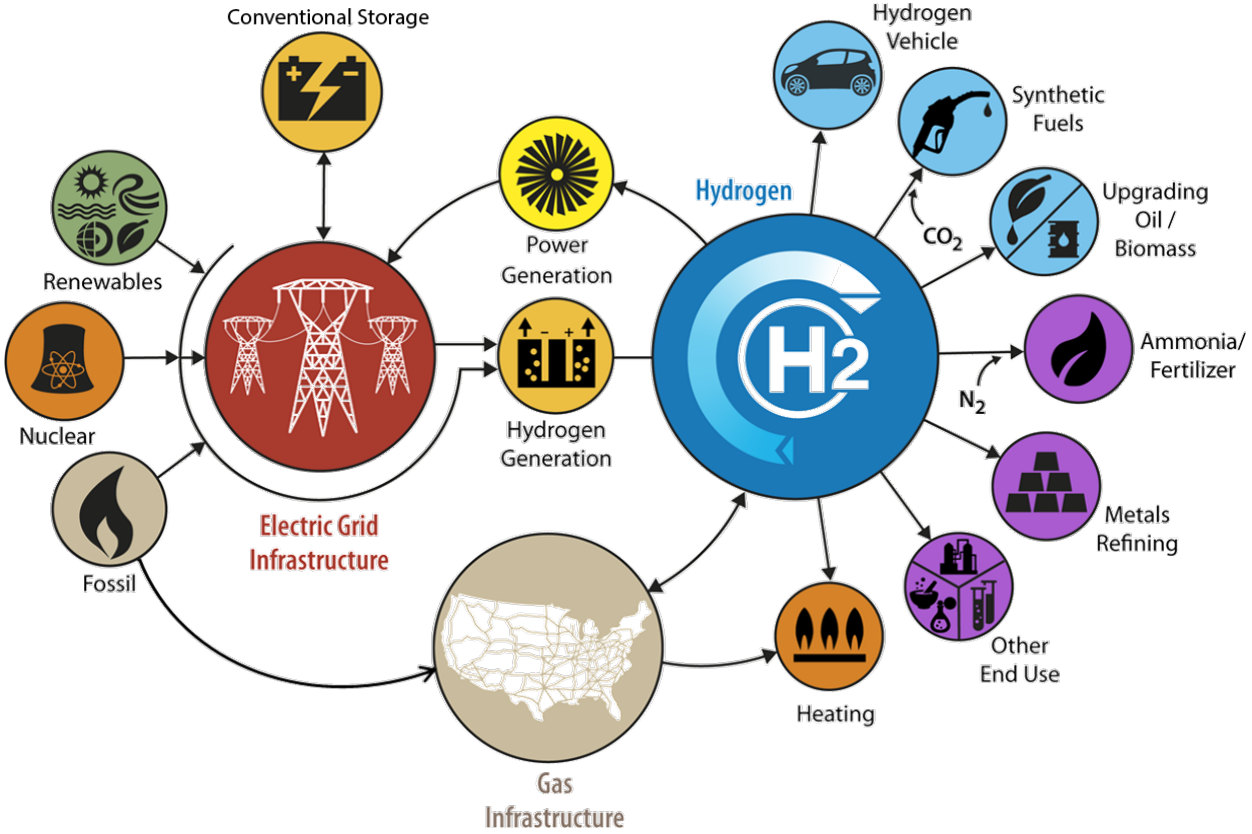
Negative Electricity Prices

Curtailment often coincides with negative prices; negative price times are also increasing



Source: 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)

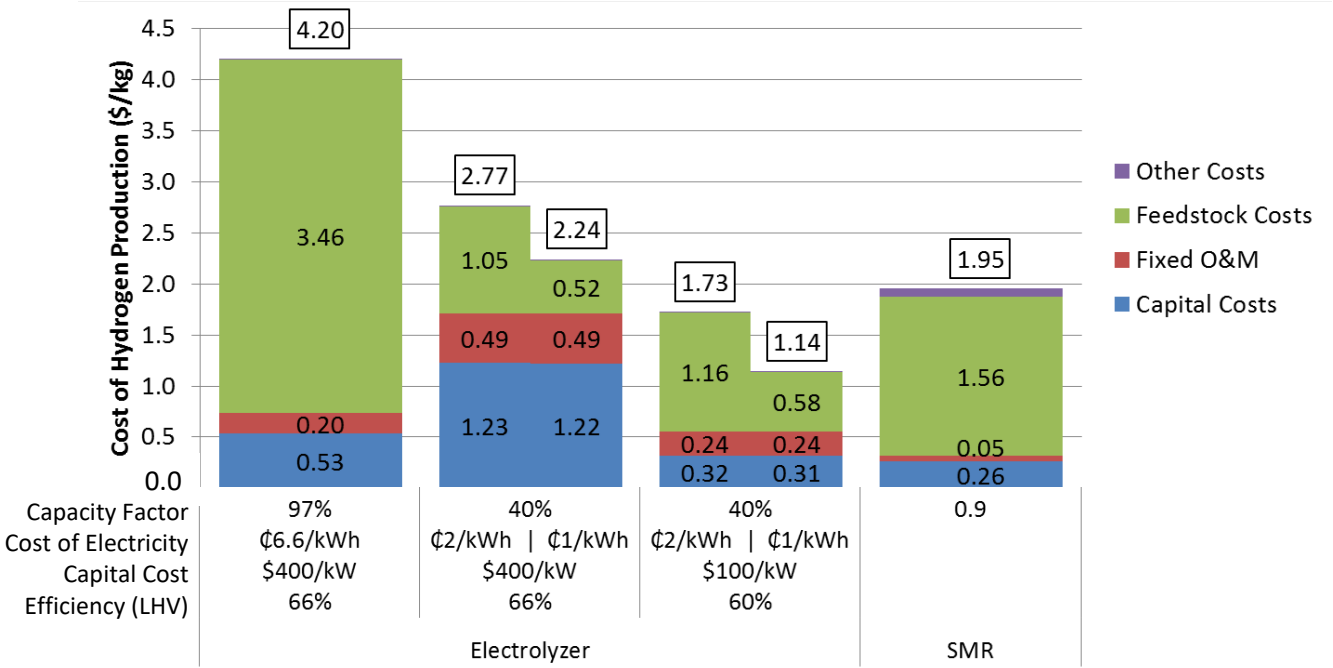
H2@Scale Opportunity



- Interface opportunities
- Value propositions lie across the make, move, use, and store focus areas
- Key drivers:
  - Markets
  - Linkages
  - Partners

Technology Development: Electrolysis

Potential Levelized Costs of H_2 Production

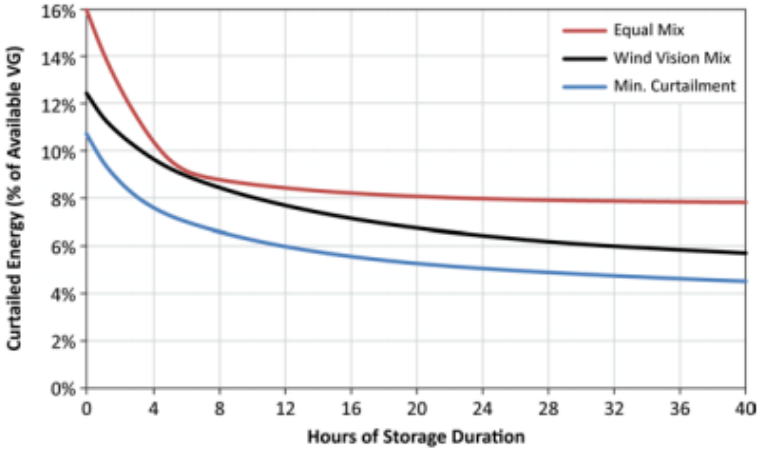


- Electrolytic hydrogen has the potential to be cost competitive
- Need H_2 market access
- Business opportunities:
  - H_2 production
  - Electrolysis equipment and supply chain

Source: Bryan Pivovar "Introduction to H2@Scale" Presentation at 2017 DOE Hydrogen and Fuel Cells Program Review. https://www.energy.gov/sites/prod/files/2017/06/f34/fcto_june_2017_h2_scale_review_pivovar.pdf (June 9, 2017)

Seasonal Storage Opportunity

- Analysis at 55% penetration of wind and solar in ERCOT with 8.5 GW of storage capacity (⅓ of peaking capacity)
- Over 4% of electricity generated by wind and solar is curtailed at at 40 hours of storage duration
- Seasonal storage can overcome that limitation

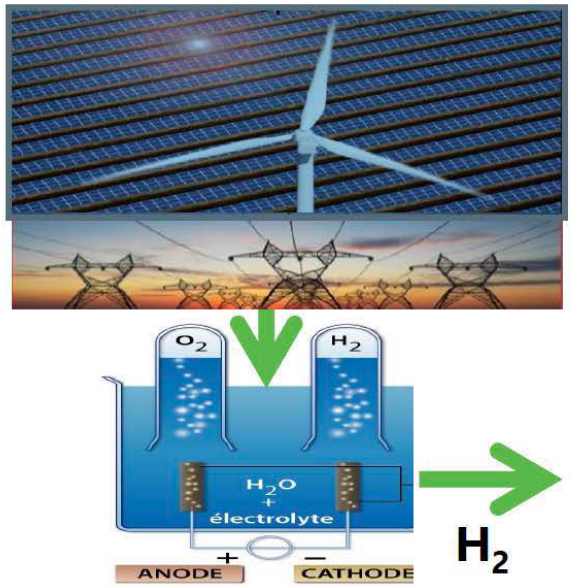


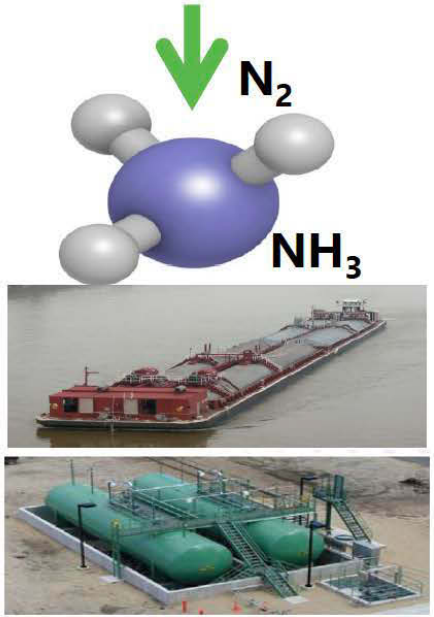
b) Fixed storage capacity (8.5 GW)

Source: P. Denholm and T. Mai "Timescales of Energy Storage Needed for Reducing Renewable Energy Curtailment" NREL/TP-6A20-68960. https://www.nrel.gov/docs/fy17osti/68960.pdf (September 2017)

Growing Opportunities for Ammonia

A large transport, storage, and distribution network exists & can leverage additional opportunities

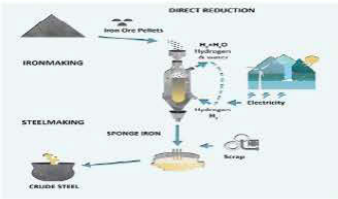




Feedstock fertilizers & other industries

Fuel

Carrier of H_2 for, e.g., iron & steel



Credit: Cedric Philibert "Green Hydrogen for the Chilean Energy Transition" (4 September 2018)

Thank you

www.nrel.gov

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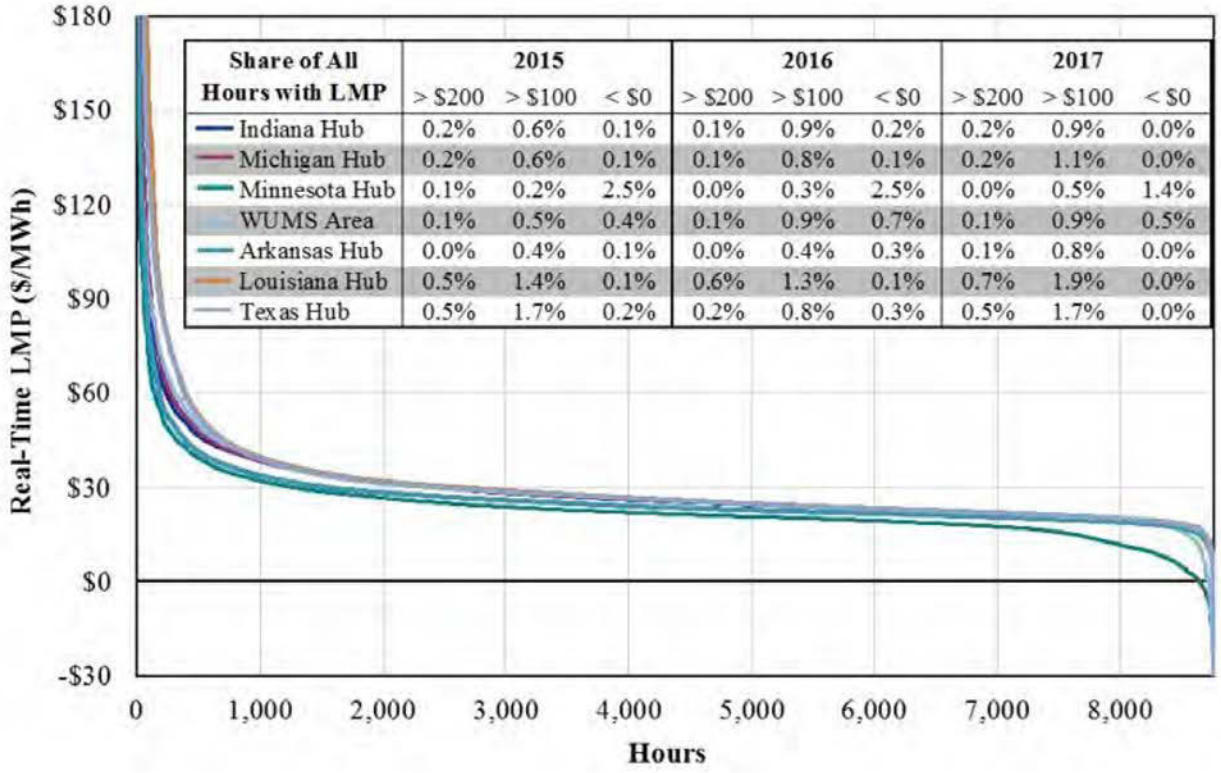
Electricity Prices are Getting More Volatile

Figure A2: Real-Time Energy Price-Duration Curve
2017



Share of All Hours with LMP	2015			2016			2017		
	> $200	> $100	< $0	> $200	> $100	< $0	> $200	> $100	< $0
Indiana Hub	0.2%	0.6%	0.1%	0.1%	0.9%	0.2%	0.2%	0.9%	0.0%
Michigan Hub	0.2%	0.6%	0.1%	0.1%	0.8%	0.1%	0.2%	1.1%	0.0%
Minnesota Hub	0.1%	0.2%	2.5%	0.0%	0.3%	2.5%	0.0%	0.5%	1.4%
WUMS Area	0.1%	0.5%	0.4%	0.1%	0.9%	0.7%	0.1%	0.9%	0.5%
Arkansas Hub	0.0%	0.4%	0.1%	0.0%	0.4%	0.3%	0.1%	0.8%	0.0%
Louisiana Hub	0.5%	1.4%	0.1%	0.6%	1.3%	0.1%	0.7%	1.9%	0.0%
Texas Hub	0.5%	1.7%	0.2%	0.2%	0.8%	0.3%	0.5%	1.7%	0.0%

- **Hours with energy at very low and very high prices are increasing**
- **Other revenue streams (e.g., capacity, services) are becoming more critical**
- **Impacting generators' operations**

Source: Potomac Economics 2017 State of the Market Report for the MISO Electricity Market – Analytic Appendix (June 2018)

Example of an Ammonia Opportunity

- BASF and Yara opened a low-carbon ammonia plant in April
- Freeport, TX
- Primary hydrogen supply:
  - By-product from Dow's ethylene cracking units
- Economic drivers:
  - Greener ammonia
- Linked to hydrogen pipeline and storage projects
- Reduction based on carbon credits

Source: 2018; https://ammoniaindustry.com/yara-and-basf-open-low-carbon-ammonia/