# Ammonia: Opportunities for Grid Support

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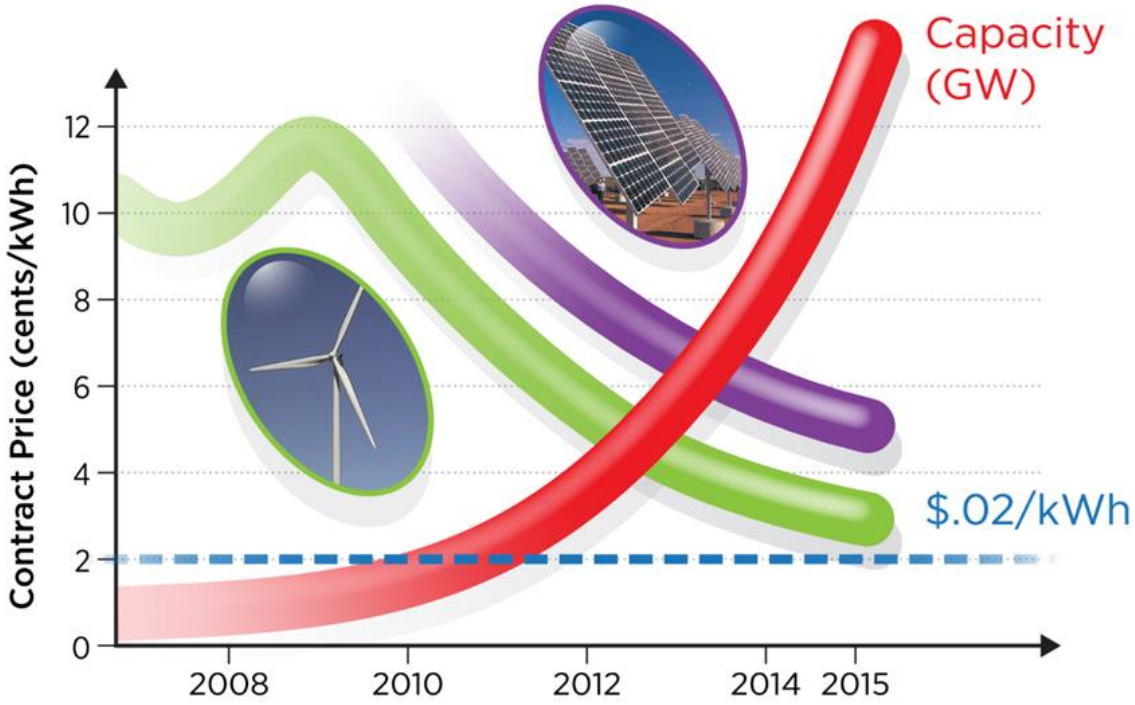
# Technology Development is Impacting the Grid

- 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** | | | |

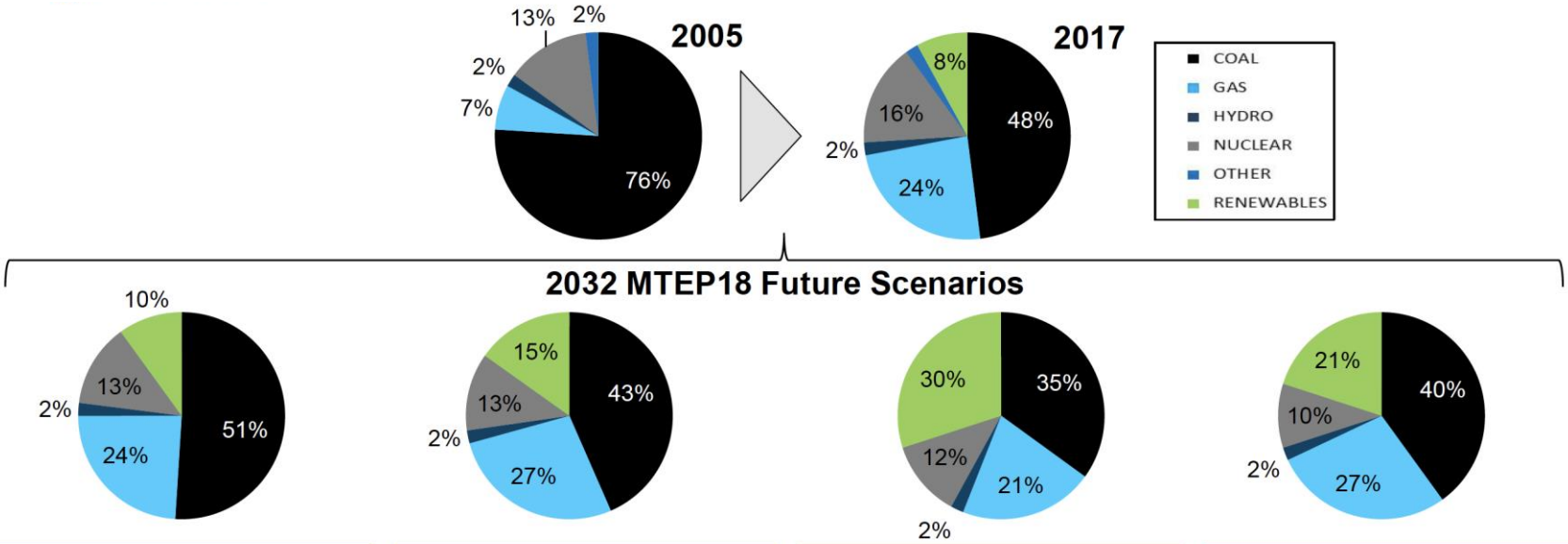
Indiana NIPSCO IRP Pricing

- **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.

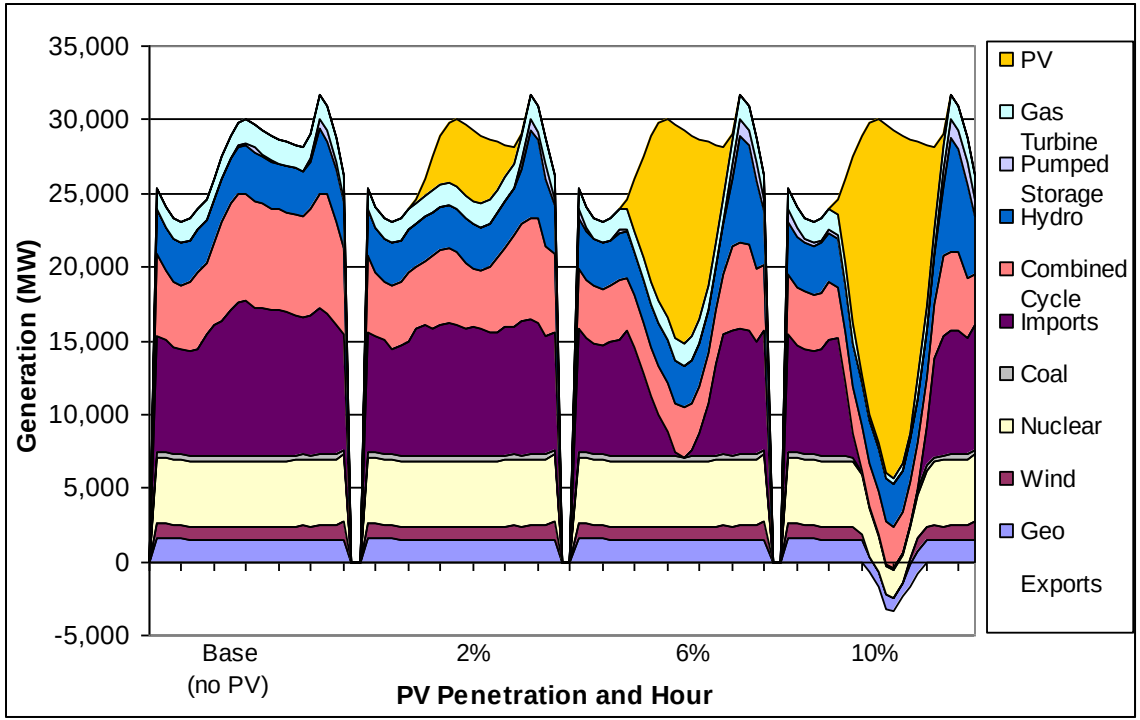
Source: Bakke, et al "Evolution of the Grid in the MISO region" (Nov 7, 2017)

# Need for Additional Grid Flexibility

Increased renewables penetration can lead to

1) over generation / curtailment

2) unprecedented ramp rates for dispatchable generation

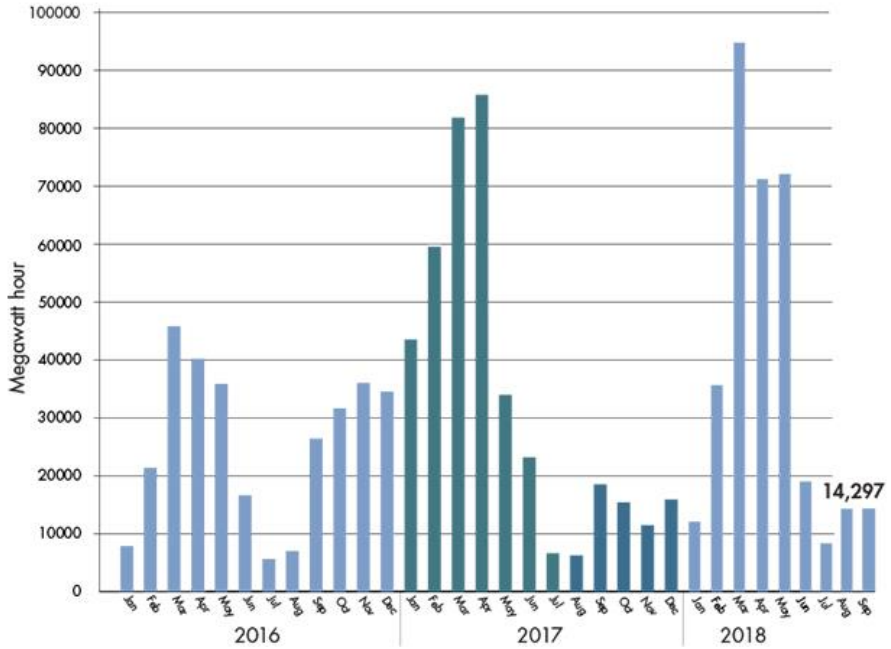



Denholm, P.; Margolis, R.M.; Milford, J. "Production Cost Modeling for High Levels of Photovoltaics Penetration." NREL/TP-581-42305. Golden, CO: National Renewable Energy Laboratory. https://www.nrel.gov/docs/fy08osti/42305.pdf (February 2008)

# 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

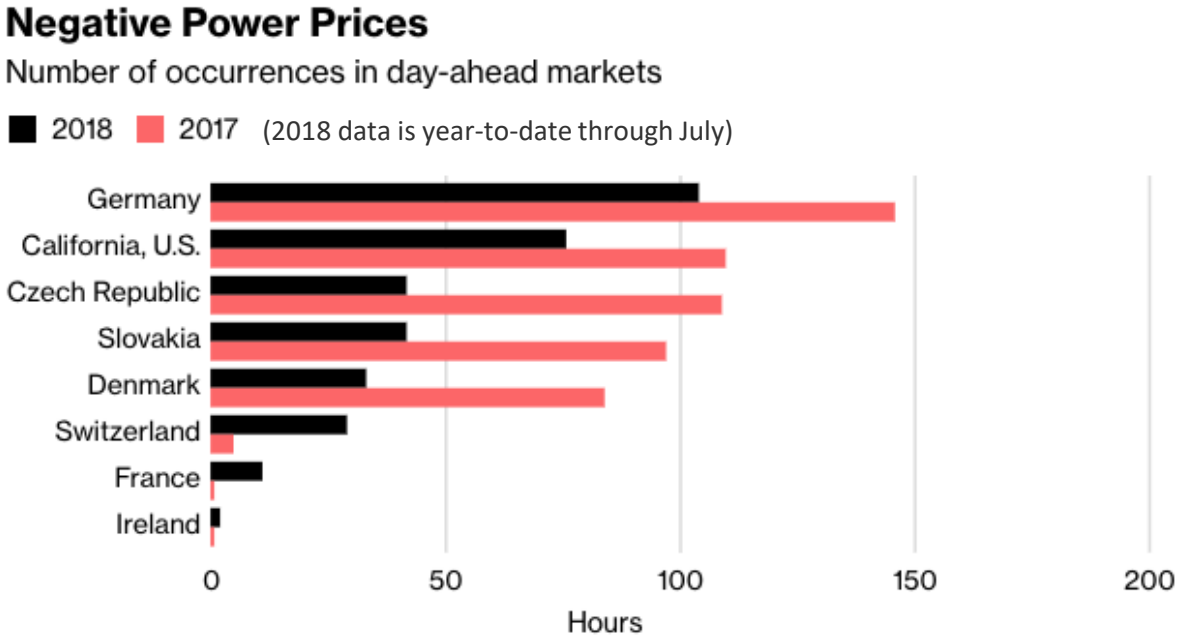
Monthly Curtailment in California




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

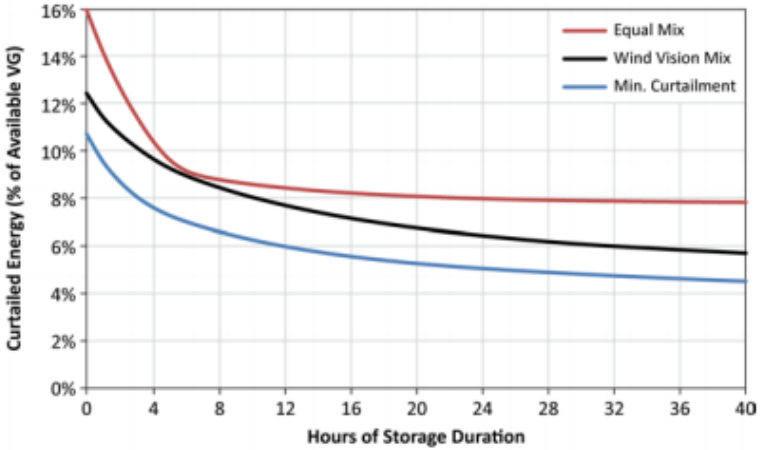
Curtailment often coincides with negative prices; negative price times are also increasing




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)

# Seasonal Storage Opportunity

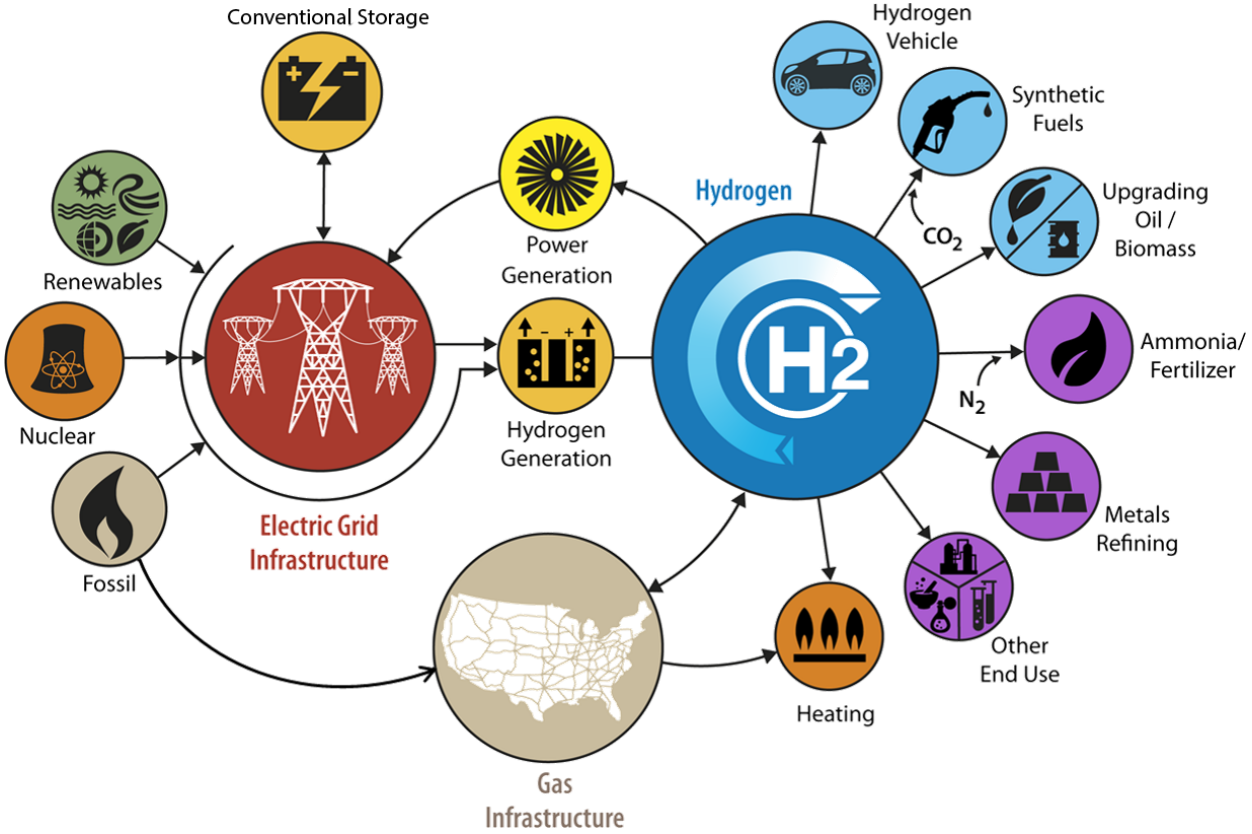
- Analysis at 55% penetration of wind and solar in ERCOT with 8.5 GW of storage capacity (⅓ of peaking capacity)
- Over 4% of electricity generated by wind and solar is curtailed at at 40 hours of storage duration
- Seasonal storage can overcome that limitation




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)

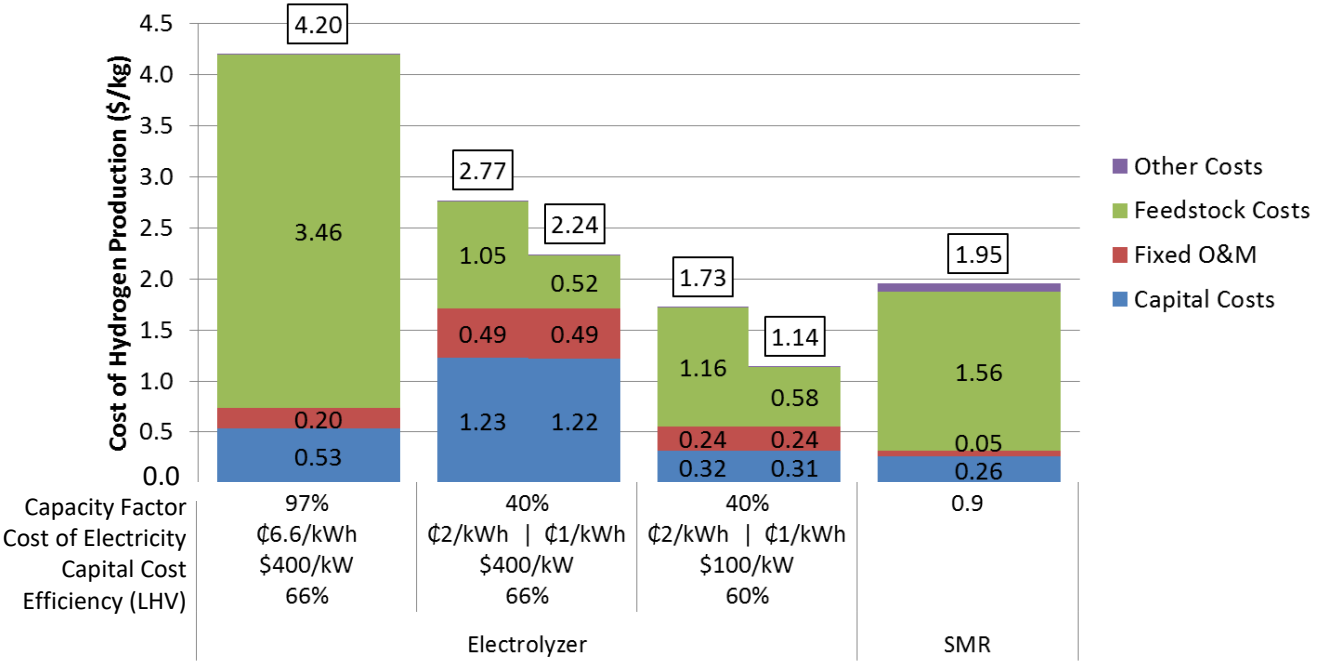
# H2@Scale Opportunity




- **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

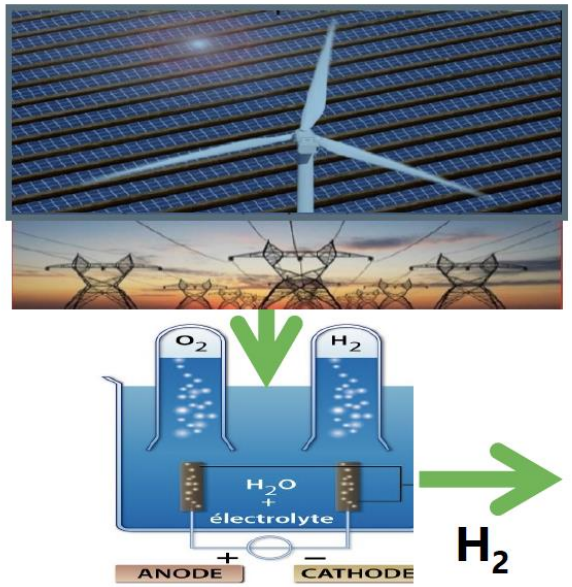


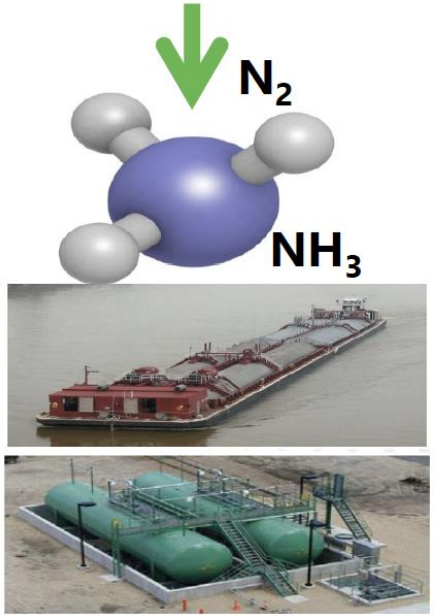

- **Electrolytic hydrogen has the potential to be cost competitive**
- **Need $H_2$ market access**
- **Business opportunities:**
  - **$H_2$ production**
  - **Electrolysis equipment and supply chain**

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)

# Growing Opportunities for Ammonia

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

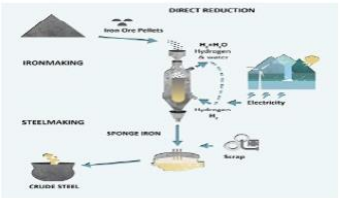



**Feedstock fertilizers & other industries**

**Fuel**

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




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

# Thank you

**www.nrel.gov**

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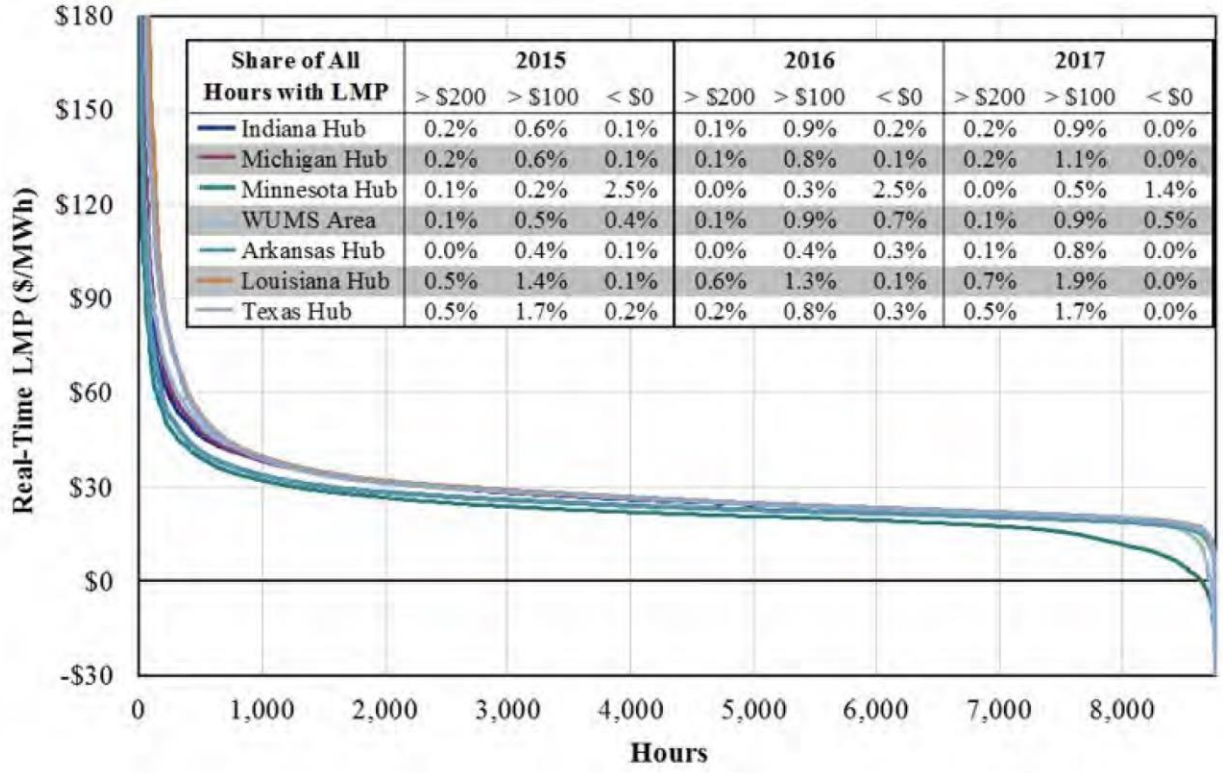
# Electricity Prices are Getting More Volatile

**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)

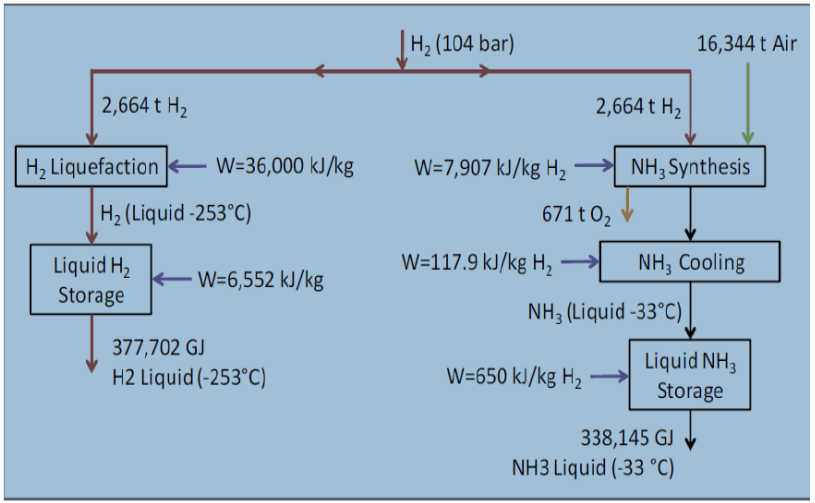
# Example of an Ammonia Opportunity

- 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/

# Storing $H_2$ and $NH_3$

| Storage | Tank cap. | Density (Kg/m³) | Vol. density (MJ/l) | Cost ($/GJ) 182 d. |
|---|---|---|---|---|
| $LH_2$ (-253°C) | 900 t | 72.41 | 8.685 | 99 |
| $H_2$ 350 bar | 90 t* | 23.65 | 2.837 | |
| $H_2$ 700 bar | | 39.69 | 4.761 | |
| $LNH_3$ (-33°C) | 60 kt | | 15.37 | 4 |
| $NH_3$ 9-17 bar | 270 t | | 13.77 | |



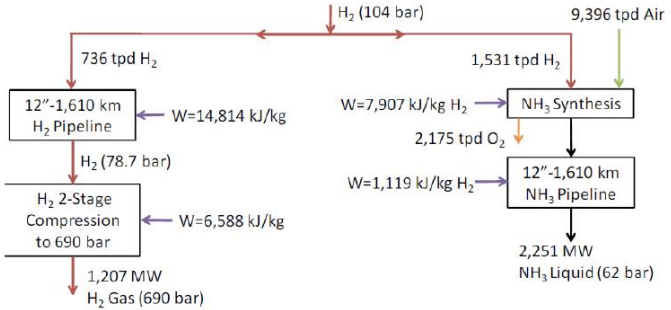

* In tanks. Can be much more in salt caverns

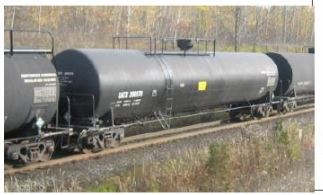
Credit: Cedric Philibert "Green Hydrogen for the Chilean Energy Transition" (4 September 2018)

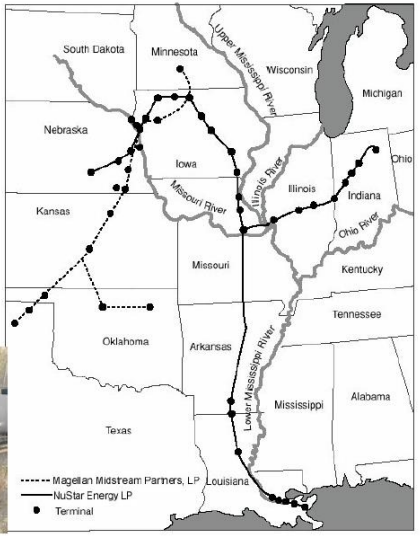
# Transporting $H_2$ and $NH_3$

- Trailer trucks: $CH_2$: 48 GJ; $LH_2$: 553 GJ; $NH_3$: 600 GJ

| 1610 km pipelines | Efficiency | Cost ($/kg $H_2$) | Carrying capacity |
|---|---|---|---|
| $H_2$ | 86.9% | 0.70-3.22 | 1,207 MW |
| $NH_3$ | 93.4%* | 0.194 | 2,251 MW |






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