H2@Scale and Tightly-Coupled Nuclear-Renewable Hybrid Energy Systems

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Nuclear and Renewable Energy Resources

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:

- 1800 employees, plus 400 postdoctoral researchers, interns, visiting professionals, and subcontractors
- 327-acre campus in Golden & 305-acre National Wind Technology Center 13 miles north
- 61 R&D 100 awards. More than 1000 scientific and technical materials published annually

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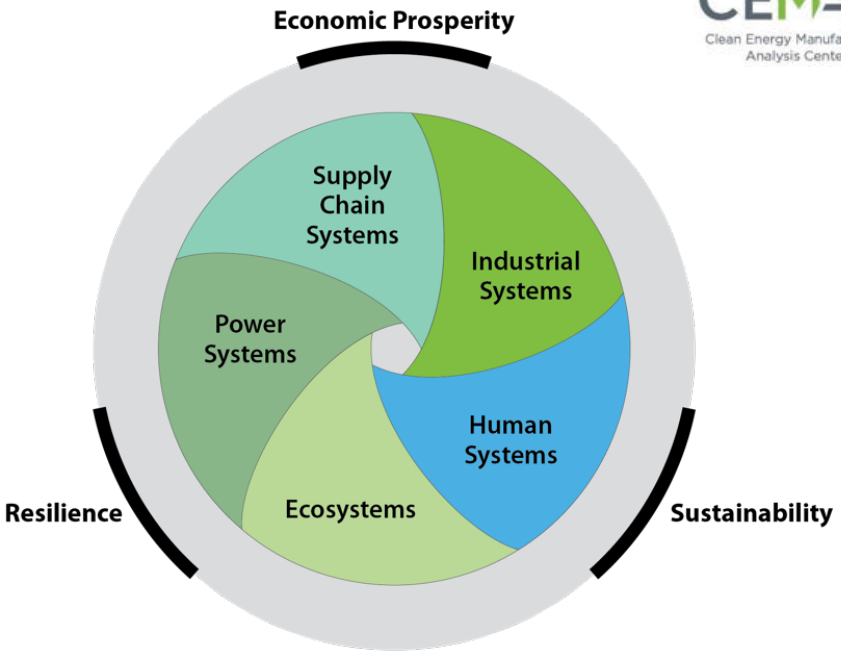
JISEA

Joint Institute for Strategic Energy Analysis

Connecting technologies, economic sectors, and continents to catalyze the transition to the 21st century energy economy.

CEMAC
Clean Energy Manufacturing Analysis Center



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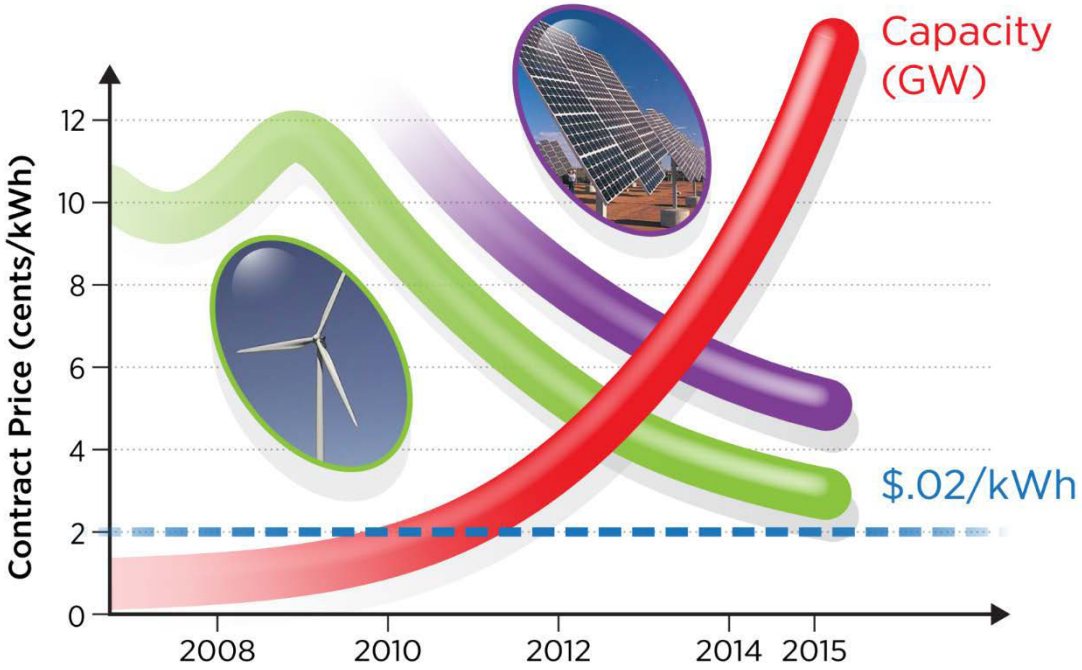
Energy System is Evolving Rapidly

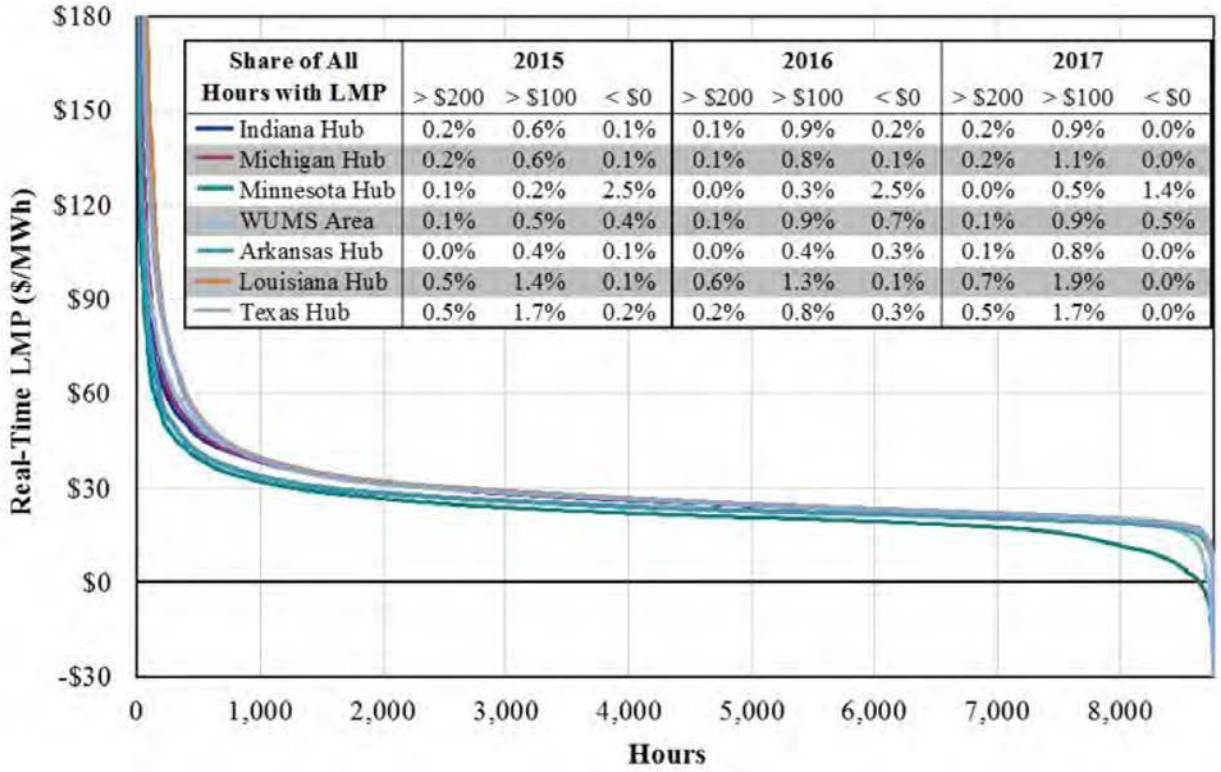


- Renewable electron prices dropping precipitously
- Penetration increasing at fast rate

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

Electricity Prices Dropping

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

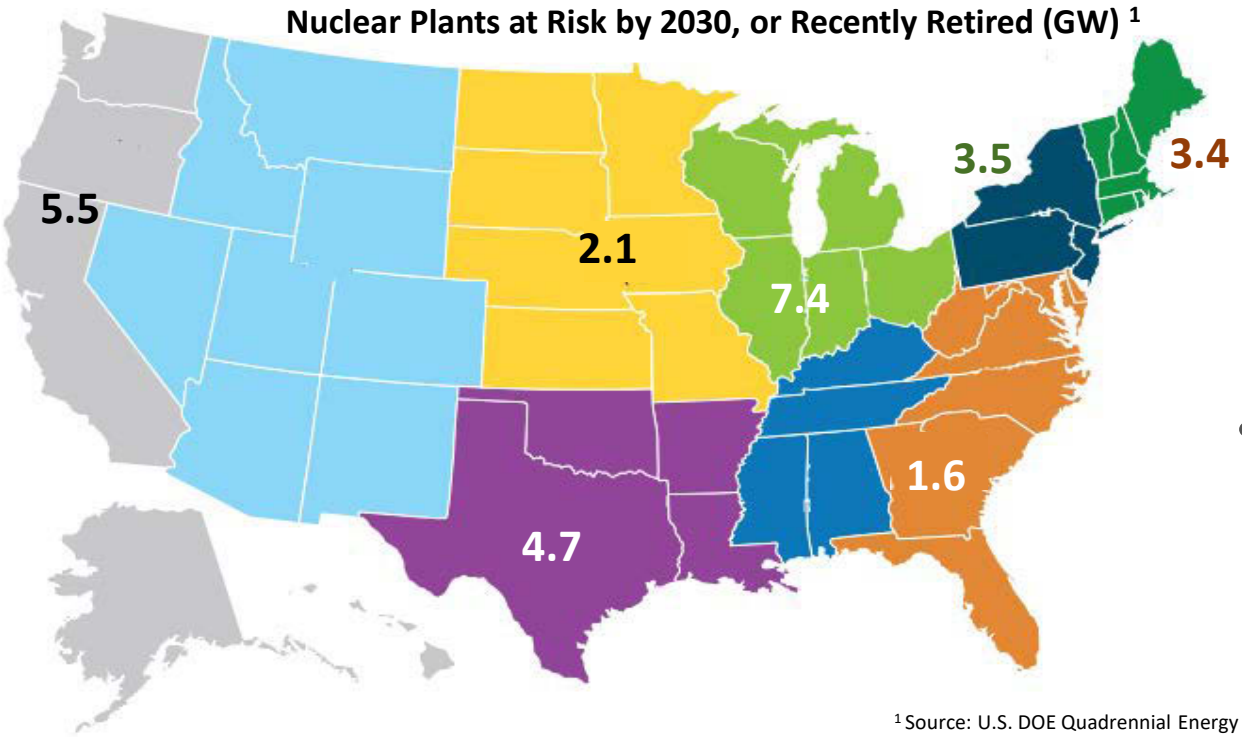


Share of All Hours with LMP	2015			2016			2017		
	> $200	> $100	< $0	> $200	> $100	< $0	> $200	> $100	< $0
Indiana Hub	0.2%	0.6%	0.1%	0.1%	0.9%	0.2%	0.2%	0.9%	0.0%
Michigan Hub	0.2%	0.6%	0.1%	0.1%	0.8%	0.1%	0.2%	1.1%	0.0%
Minnesota Hub	0.1%	0.2%	2.5%	0.0%	0.3%	2.5%	0.0%	0.5%	1.4%
WUMS Area	0.1%	0.5%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

- Low-cost, flexible natural gas generation reducing average energy price
- More hours with energy at very low and very high prices
- Other revenue streams (e.g., capacity, services) are becoming more critical

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

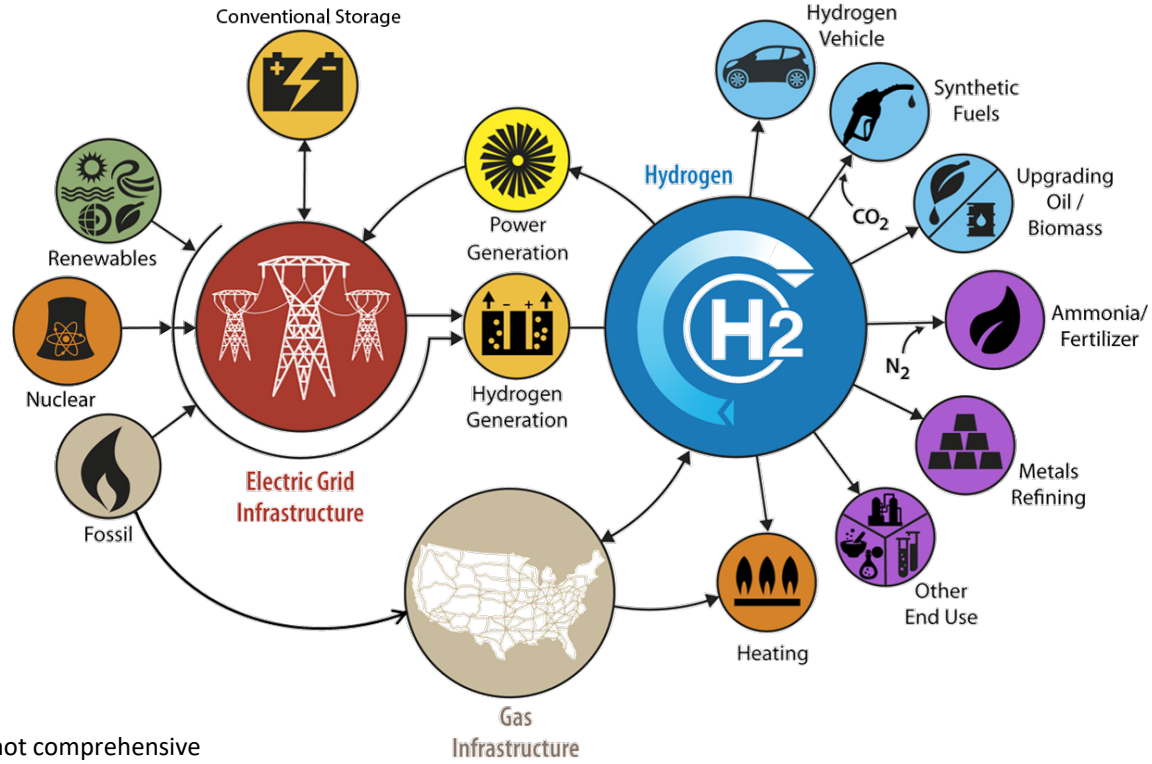
Impacting Generation Mix



- Over 20 GW of existing U.S. nuclear power generation is at risk of early retirement
- Alternative income streams may reduce retirements

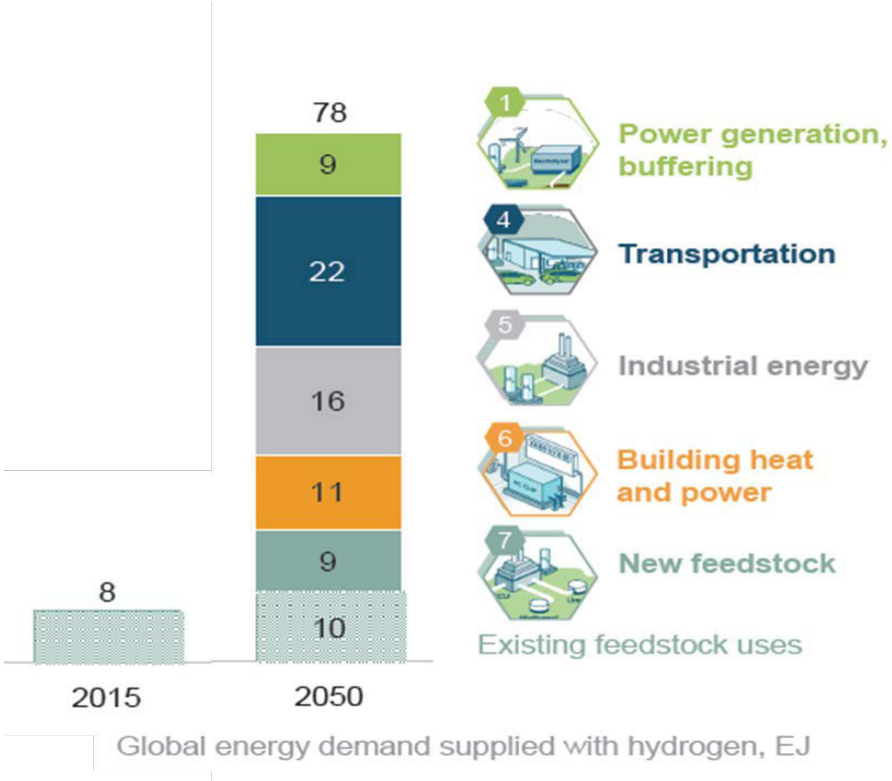
[1] Source: U.S. DOE Quadrennial Energy Review, 2017

Conceptual H2@Scale Energy System



*Illustrative example, not comprehensive

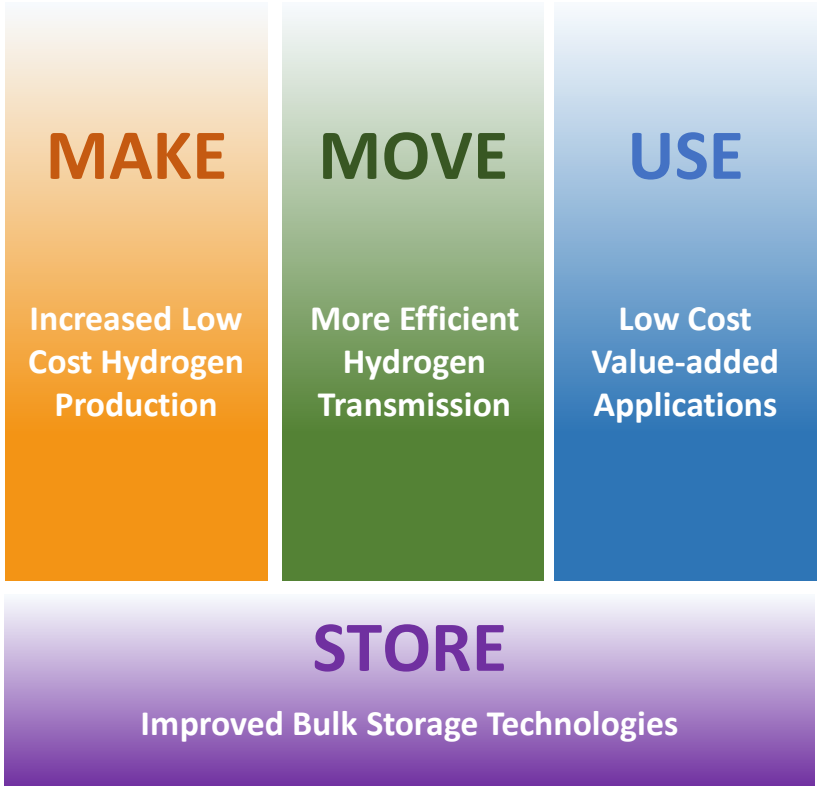
Global Hydrogen Potential



- Hydrogen Council estimates a 10-fold increase in global hydrogen use by 2050
- Key opportunities are transportation, industrial energy, and as a feedstock for chemical processing

Source: Hydrogen Council

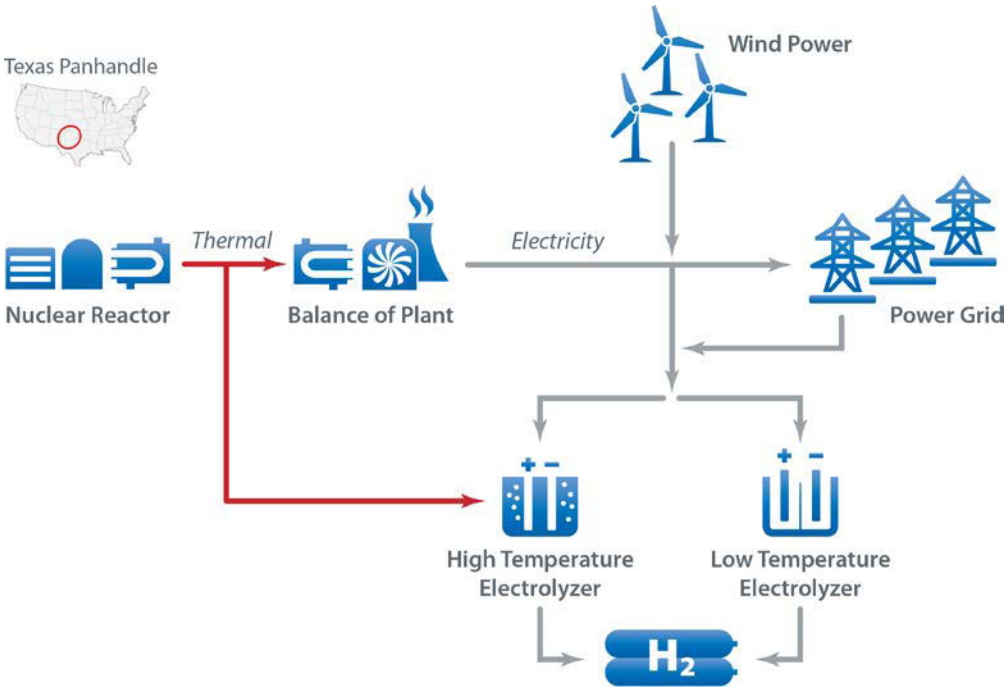
H2@Scale: U.S. Initiative



- Advancing technology to increase revenue across multiple sectors
- Industry and government co-funded projects
- Accelerating early stage research & development

Source: Satyapal, Sunita. "Hydrogen and Fuel Cell Program Overview" Presented at the Fuel Cell Technologies Office's Annual Merit Review. (June 13, 2018) https://www.hydrogen.energy.gov/pdfs/review18/01_satyapal_plenary_2018_amr.pdf

N-R HESs Producing Hydrogen



- Analyzed the economic potential of two tightly-coupled nuclear-renewable hybrid energy systems producing hydrogen
  - High temperature electrolysis (HTE) integrated via both thermal and electrical energy
  - Low temperature electrolysis (LTE) integrated via electrical energy only

Source: Ruth, Mark, Cutler, Dylan, Flores-Espino, Francisco, and Stark, Greg. *The Economic Potential of Nuclear-Renewable Hybrid Energy Systems Producing Hydrogen* (2017). NREL/TP-6A50-66764. http://www.nrel.gov/docs/fy17osti/66764.pdf

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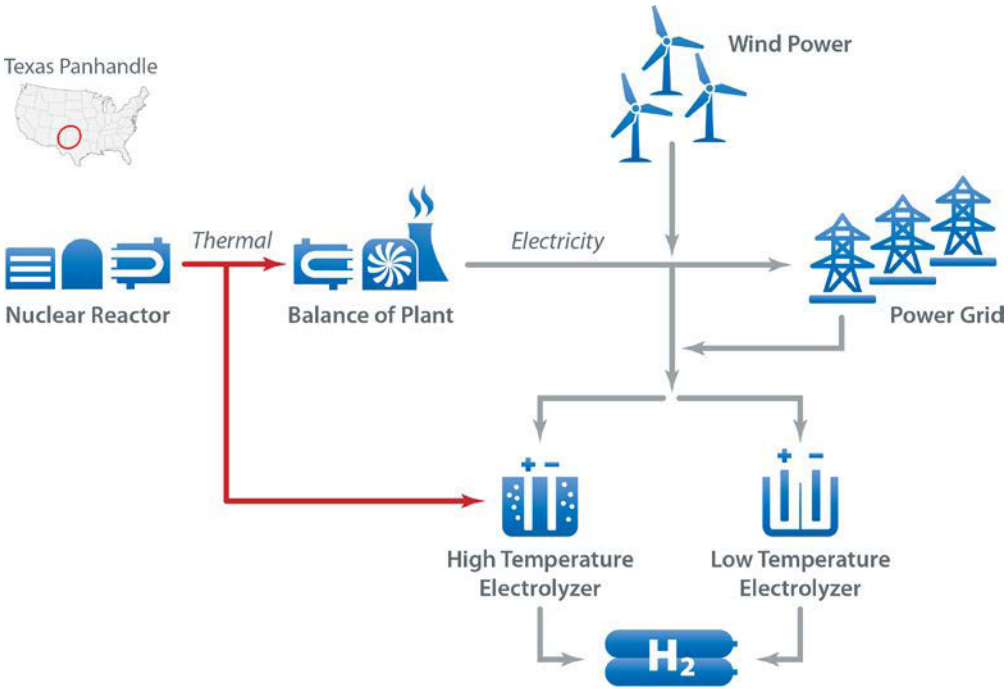

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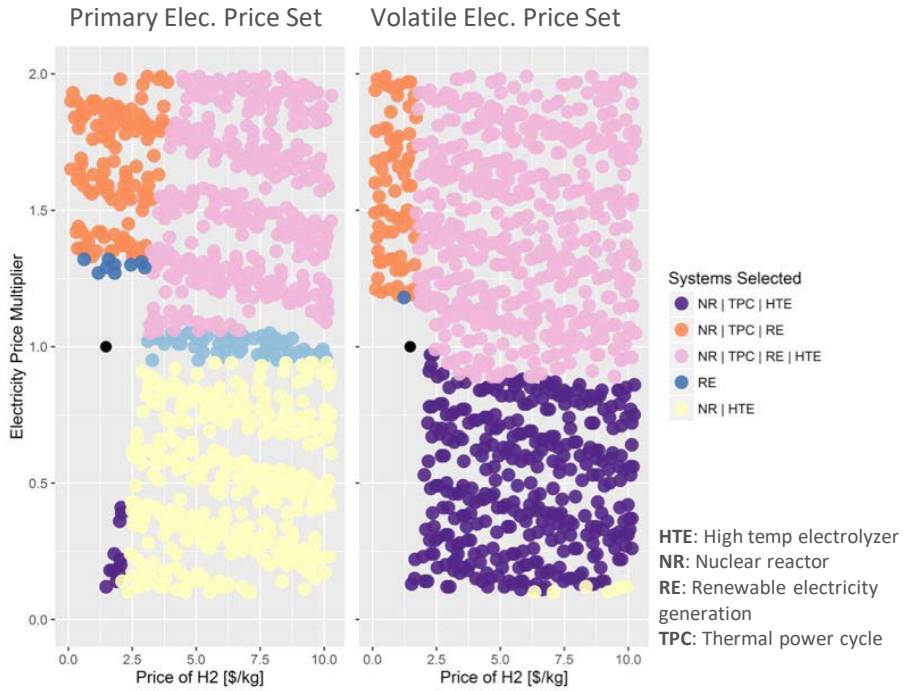
High Temperature Electrolysis N-R HES: Optimal, Profitable Configurations



HTE: High temp electrolyzer
NR: Nuclear reactor
RE: Renewable electricity generation
TPC: Thermal power cycle

Source: Ruth, Mark, Cutler, Dylan, Flores-Espino, Francisco, and Stark, Greg. *The Economic Potential of Nuclear-Renewable Hybrid Energy Systems Producing Hydrogen* (2017). NREL/TP-6A50-66764. http://www.nrel.gov/docs/fy17osti/66764.pdf

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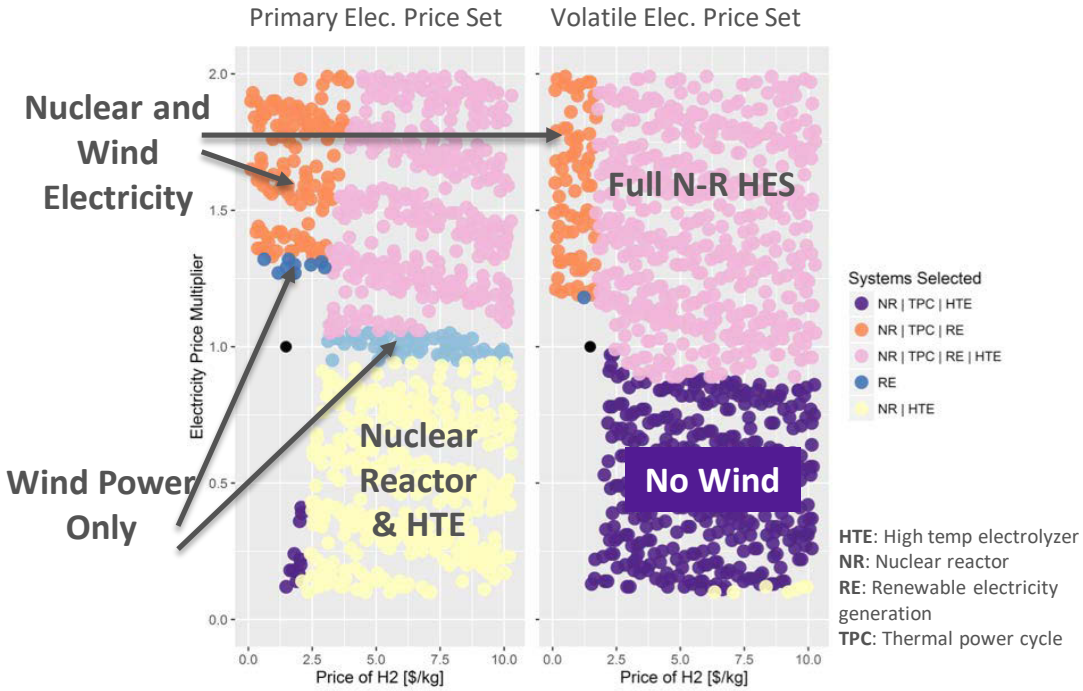

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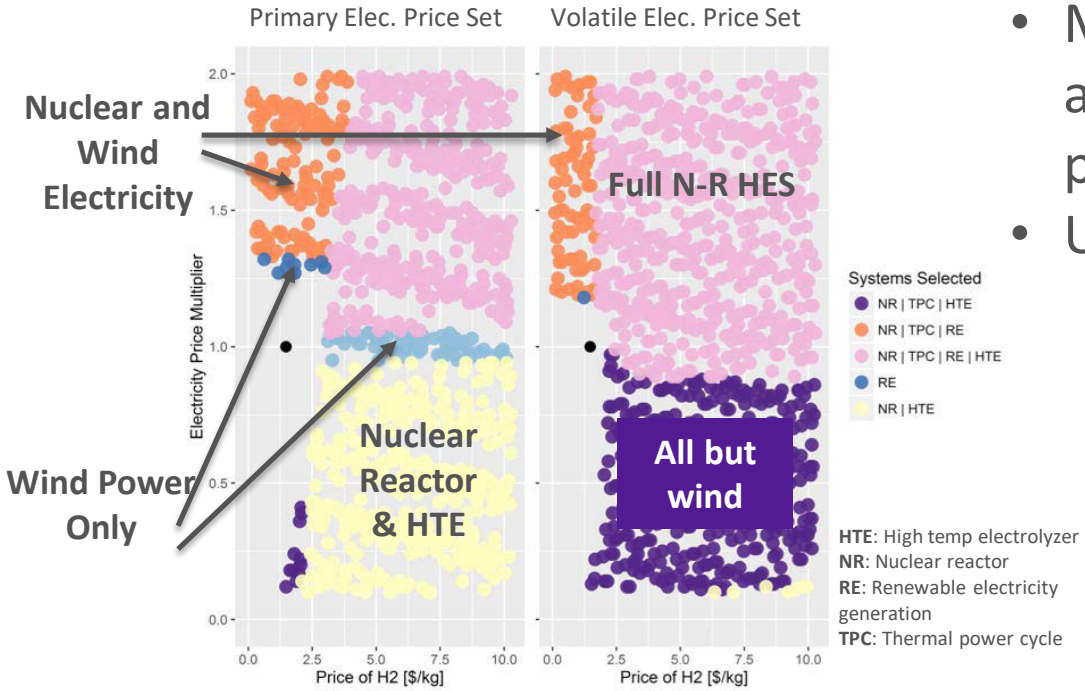
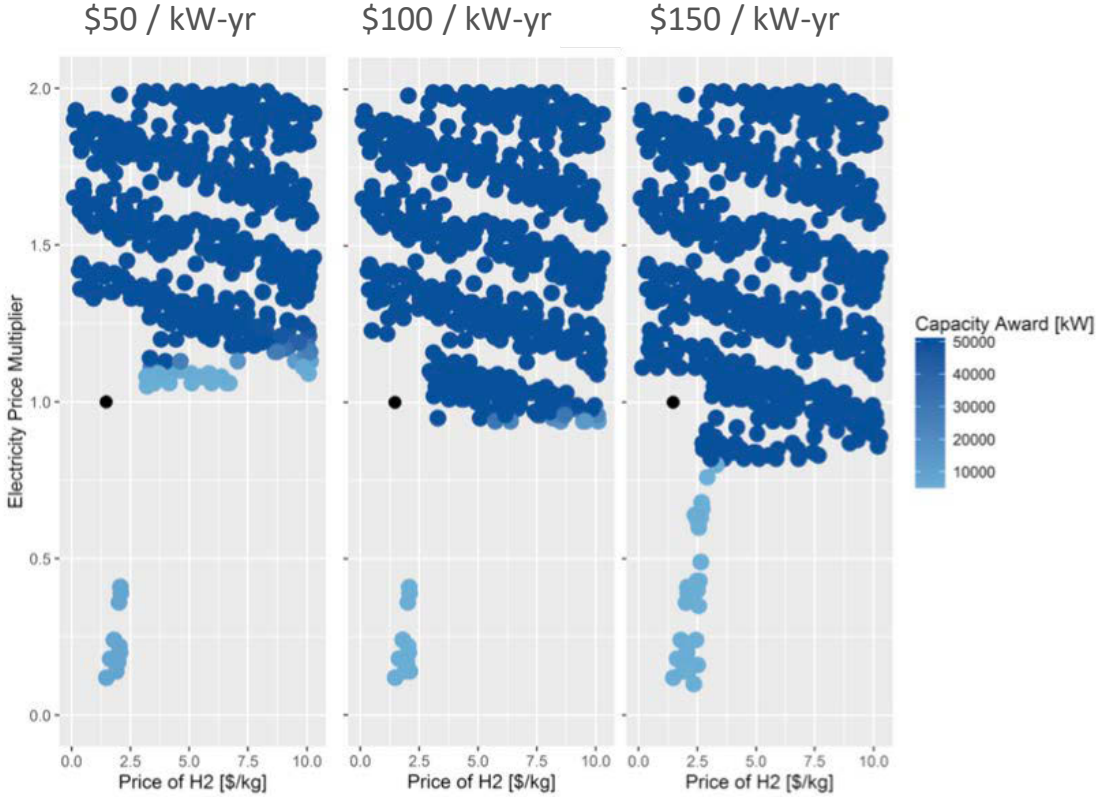


- Many combinations of electricity and hydrogen prices have profitable configurations
- Under volatile electricity prices
  - More cases at lower hydrogen prices are profitable
  - More scenarios with nuclear power that provides electricity and supports grid resources

Source: Ruth, Mark, Cutler, Dylan, Flores-Espino, Francisco, and Stark, Greg. *The Economic Potential of Nuclear-Renewable Hybrid Energy Systems Producing Hydrogen* (2017). NREL/TP-6A50-66764. http://www.nrel.gov/docs/fy17osti/66764.pdf

High Temperature Electrolysis N-R HES: Impact of Capacity Payments



- Higher capacity payments lead to more optimal configurations that provide grid support
- But a sufficient hydrogen price is still critical

Source: Ruth, Mark, Cutler, Dylan, Flores-Espino, Francisco, and Stark, Greg. *The Economic Potential of Nuclear-Renewable Hybrid Energy Systems Producing Hydrogen* (2017). NREL/TP-6A50-66764. http://www.nrel.gov/docs/fy17osti/66764.pdf

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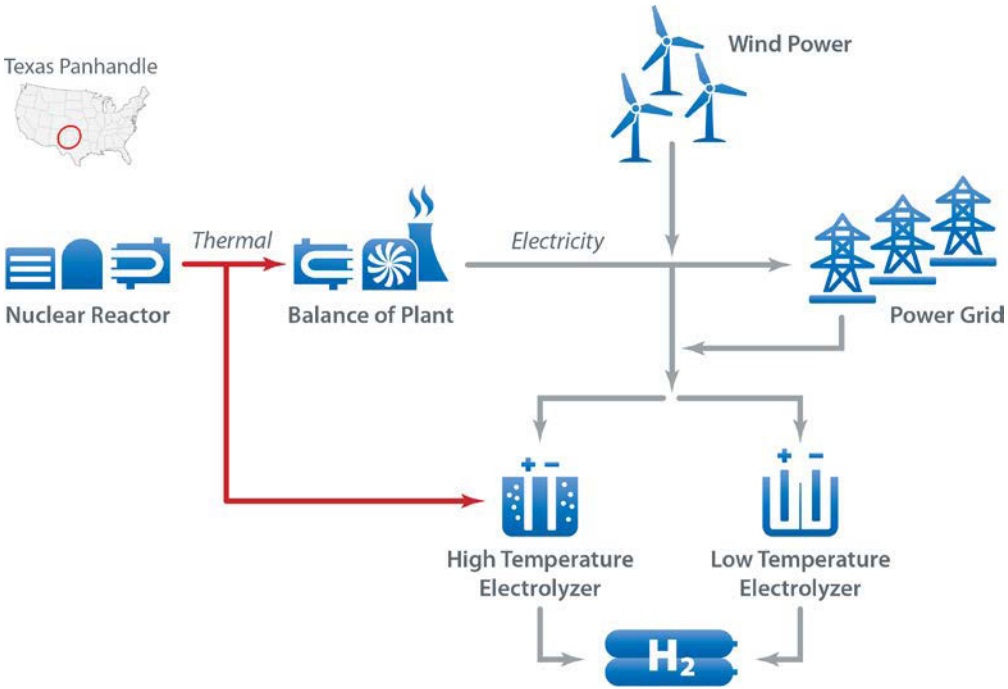

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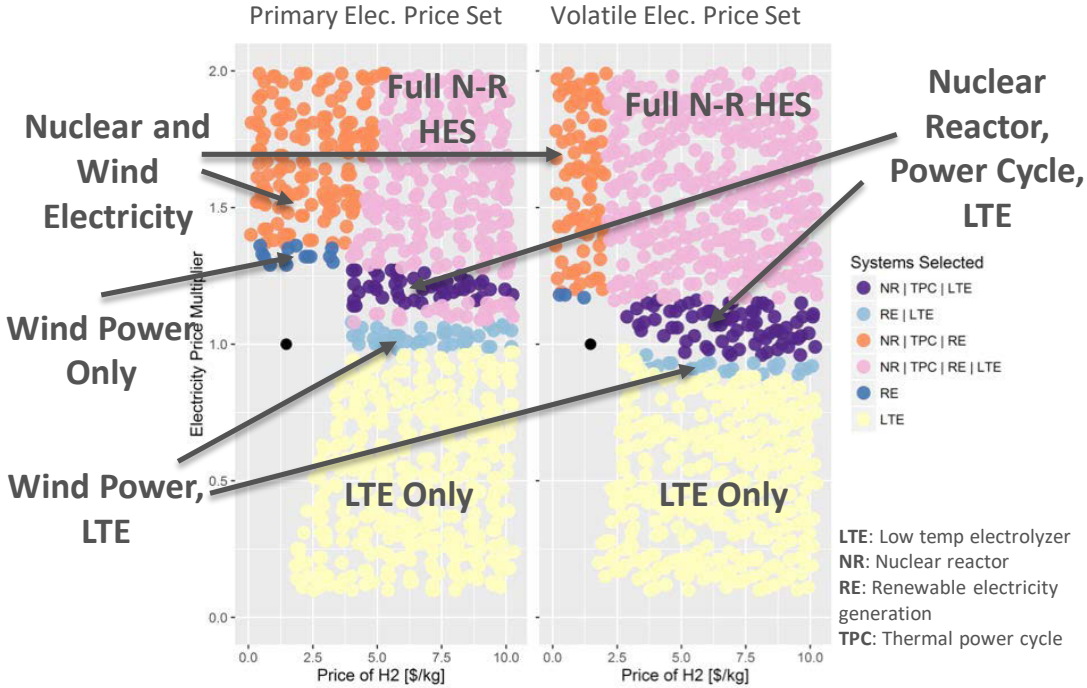
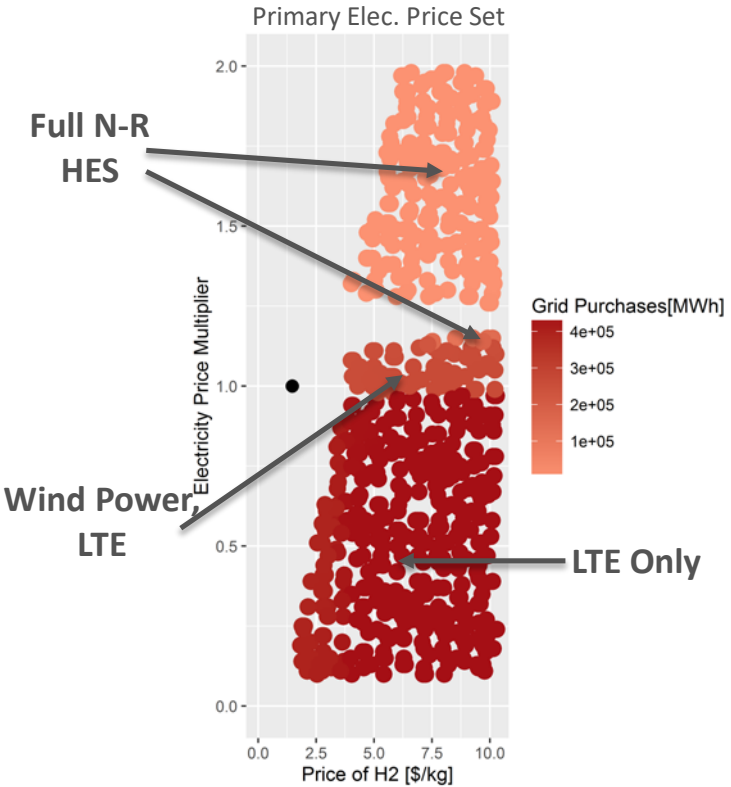
Low Temperature Electrolysis N-R HES: Optimal, Profitable Configurations



- More low-price hydrogen cases are profitable under the volatile electricity price set
- Configurations with the nuclear reactor, the thermal power cycle, and the LTE adjust their product slate each hour

Source: Ruth, Mark, Cutler, Dylan, Flores-Espino, Francisco, and Stark, Greg. *The Economic Potential of Nuclear-Renewable Hybrid Energy Systems Producing Hydrogen* (2017). NREL/TP-6A50-66764. http://www.nrel.gov/docs/fy17osti/66764.pdf

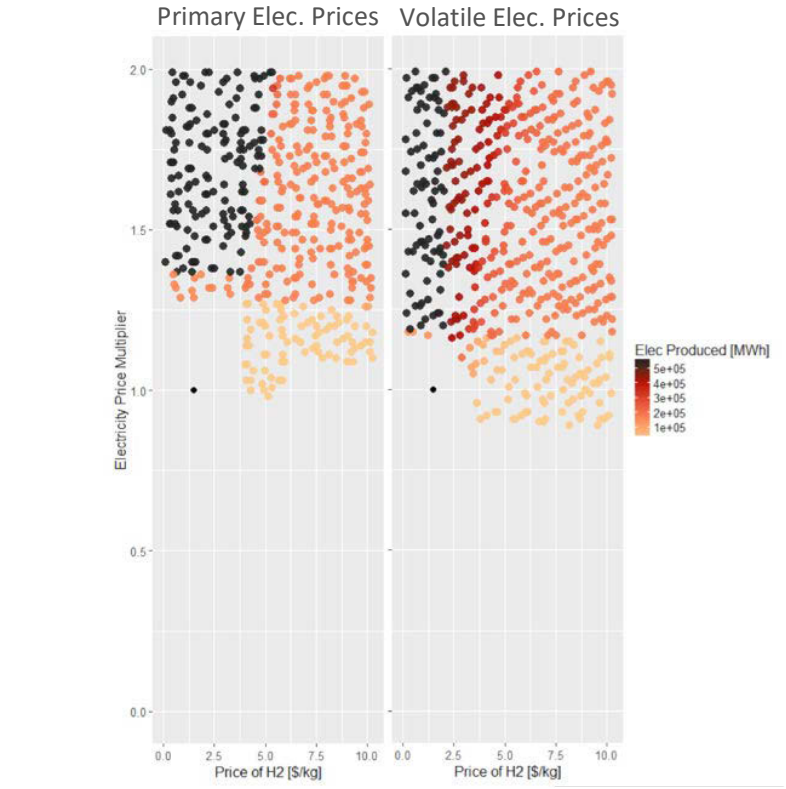
Low Temperature Electrolysis N-R HES: Purchasing Electricity



- Optimal configurations purchase electricity especially when electricity prices are low
- Configurations with wind power generation offset purchases

Source: Ruth, Mark, Cutler, Dylan, Flores-Espino, Francisco, and Stark, Greg. *The Economic Potential of Nuclear-Renewable Hybrid Energy Systems Producing Hydrogen* (2017). NREL/TP-6A50-66764. http://www.nrel.gov/docs/fy17osti/66764.pdf

Low Temperature Electrolysis N-R HES: Flexibility Increases Profitability (at Times)



- More beneficial when electricity prices are volatile
- Beneficial at high electricity price multipliers and hydrogen prices between $2.50 and $3.75/kg

Source: Ruth, Mark, Cutler, Dylan, Flores-Espino, Francisco, and Stark, Greg. *The Economic Potential of Nuclear-Renewable Hybrid Energy Systems Producing Hydrogen* (2017). NREL/TP-6A50-66764. http://www.nrel.gov/docs/fy17osti/66764.pdf

Conclusions

- Hydrogen has the potential to become an energy carrier that complements electricity.
- Analysis of nuclear-renewable hybrid energy systems (N-R HESs) producing hydrogen indicate that they may be economically viable for some market conditions. Key drivers include:
  - Hydrogen price
  - Electricity price volatility
  - Availability of a capacity payment

Thank you

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