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Opportunities and Challenges for Nuclear-Renewable Hybrid Energy Systems

Mark F. Ruth

October 4, 2021

Joint ICTP-IAEA VIRTUAL Course on Nuclear–Renewable Integrated Energy Systems: Phenomenology, Research and Development

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Publications

- Ruth, Mark, Paul Spitsen, Richard Boardman, and Shannon Bragg-Sitton. 2019. “Opportunities and Challenges for Nuclear-Renewable Hybrid Energy Systems.” Chapter in International Atomic Energy Agency TecDoc *Nuclear–Renewable Hybrid Energy Systems for Decarbonized Energy Production and Cogeneration Proceedings of a Technical Meeting*. IAEA-TECDOC-1885. https://www-pub.iaea.org/MTCD/Publications/PDF/TE-1885web.pdf.
- 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
- Ruth, Mark, Cutler, Dylan, Flores-Espino, Francisco, Stark, Greg, and Jenkin, Thomas. *The Economic Potential of Three Nuclear-Renewable Hybrid Energy Systems Providing Thermal Energy to Industry* (2016). NREL/TP-6A50-66745. http://www.nrel.gov/docs/fy17osti/66745.pdf
- Ruth, Mark, Cutler, Dylan, Flores-Espino, Francisco, Stark, Greg, Jenkin, Thomas, Simpkins, Travis, and Macknick, Jordan. *The Economic Potential of Two Nuclear-Renewable Hybrid Energy Systems*, 2016. NREL/TP-6A50-66073. http://www.nrel.gov/docs/fy16osti/66073.pdf

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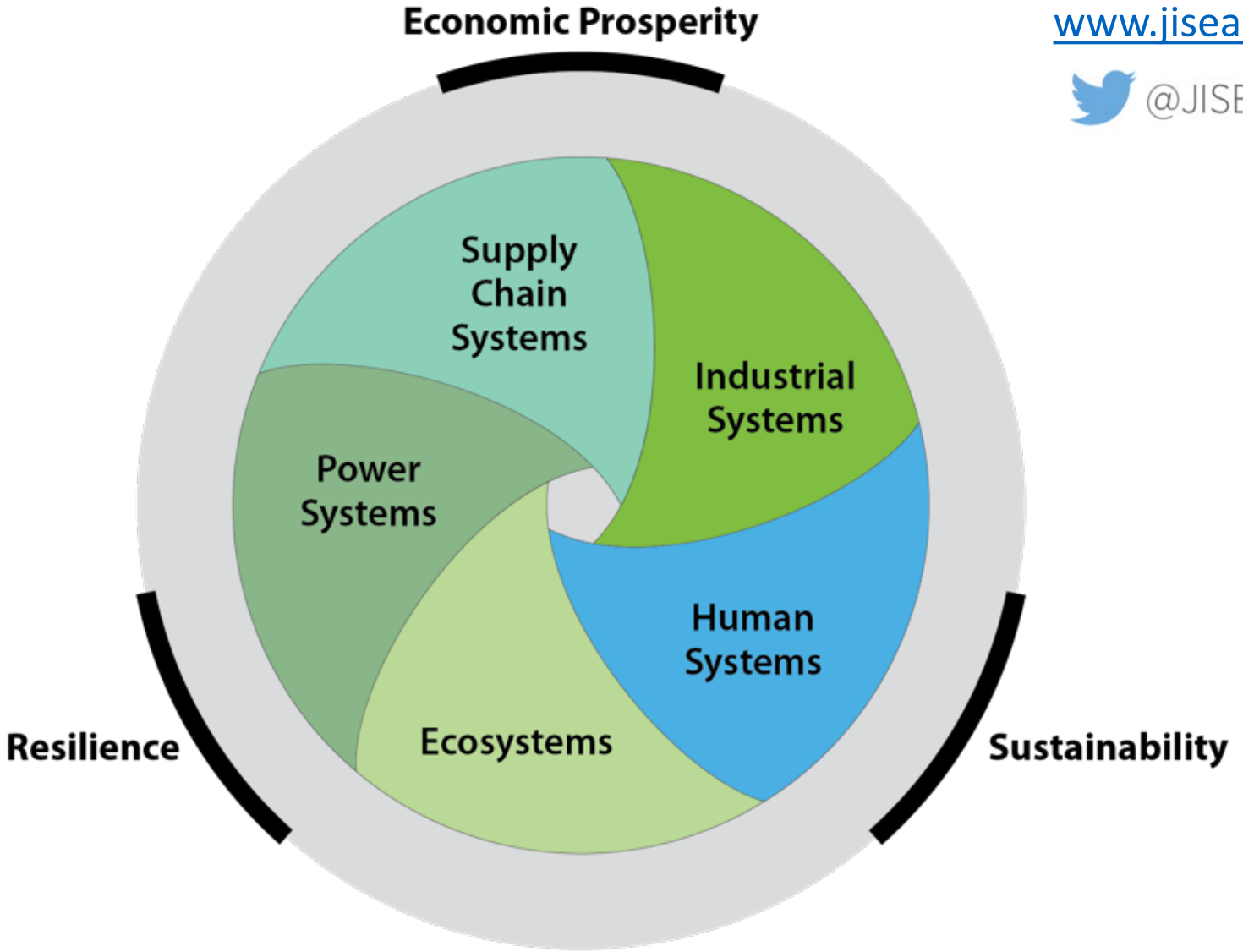

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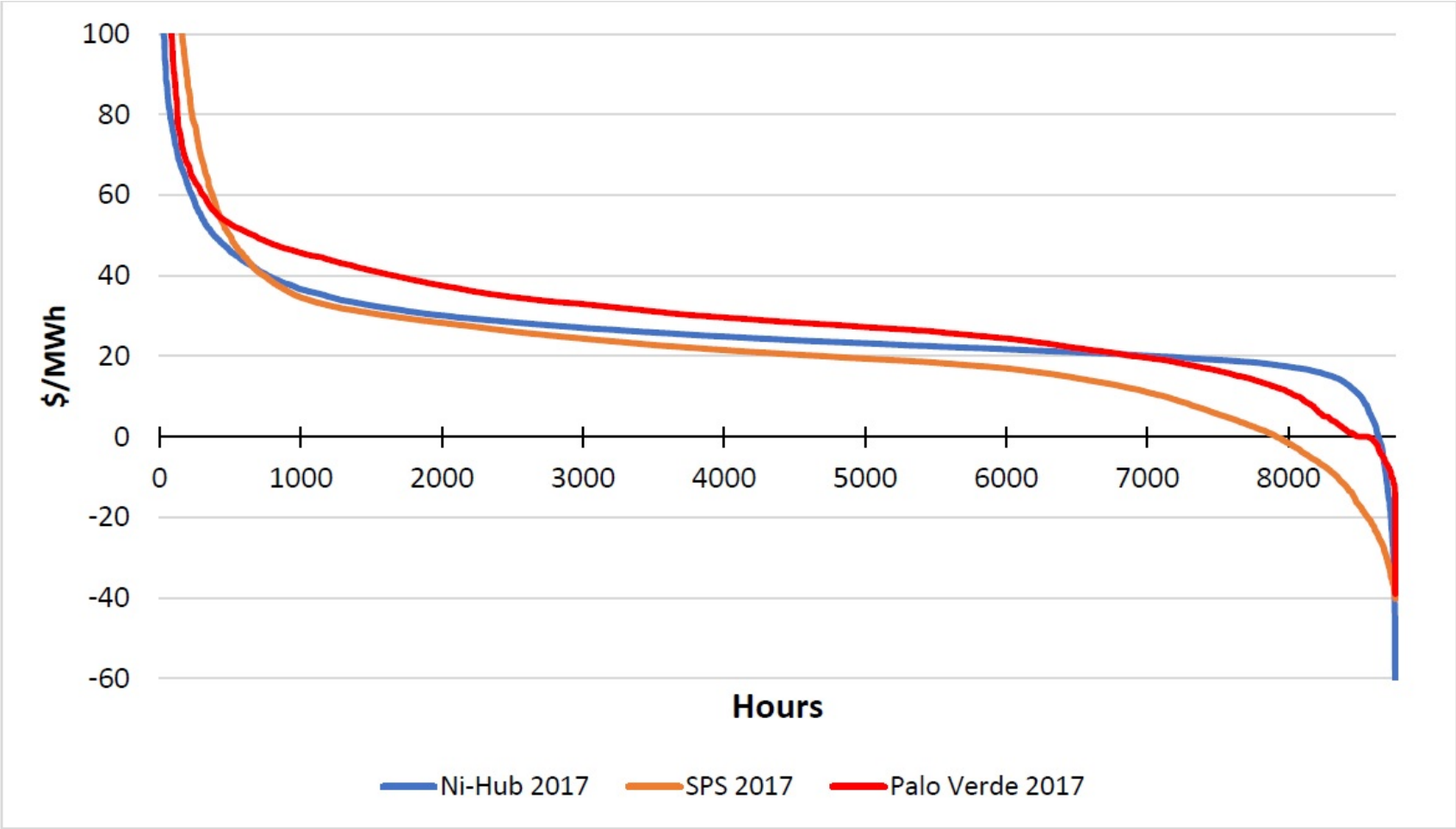
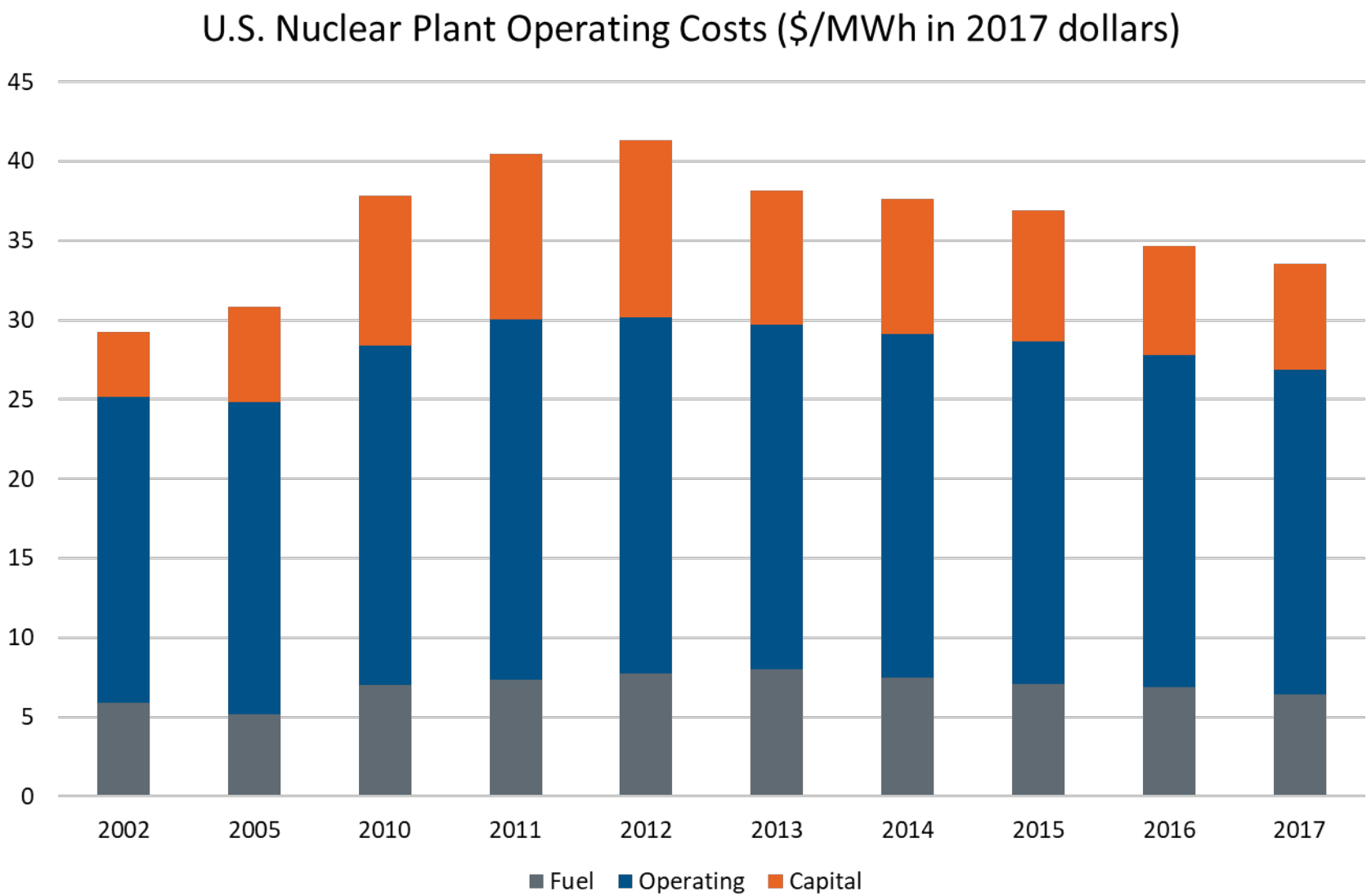
Reduced and Volatile Electricity Prices



Natural gas prices have reduced the average electricity wholesale selling price and variable renewable generation has made it more volatile.

Figure created by NREL (Daniel Levie) based on publicly available price data

Operating Costs of Nuclear Power Plants



Operating costs of nuclear plants are not negligible.

Current range is $25/MWh -- $40/MWh

Most of the cost is operators, security, and other required personnel.

Data Source: **Nuclear Energy Institute,** "Nuclear Costs in Context" https://www.nei.org/CorporateSite/media/filefolder/resources/reports-and-briefs/nuclear-costs-context-201810.pdf (June 19, 2019).

Reduced and Volatile Electricity Prices are a Challenge

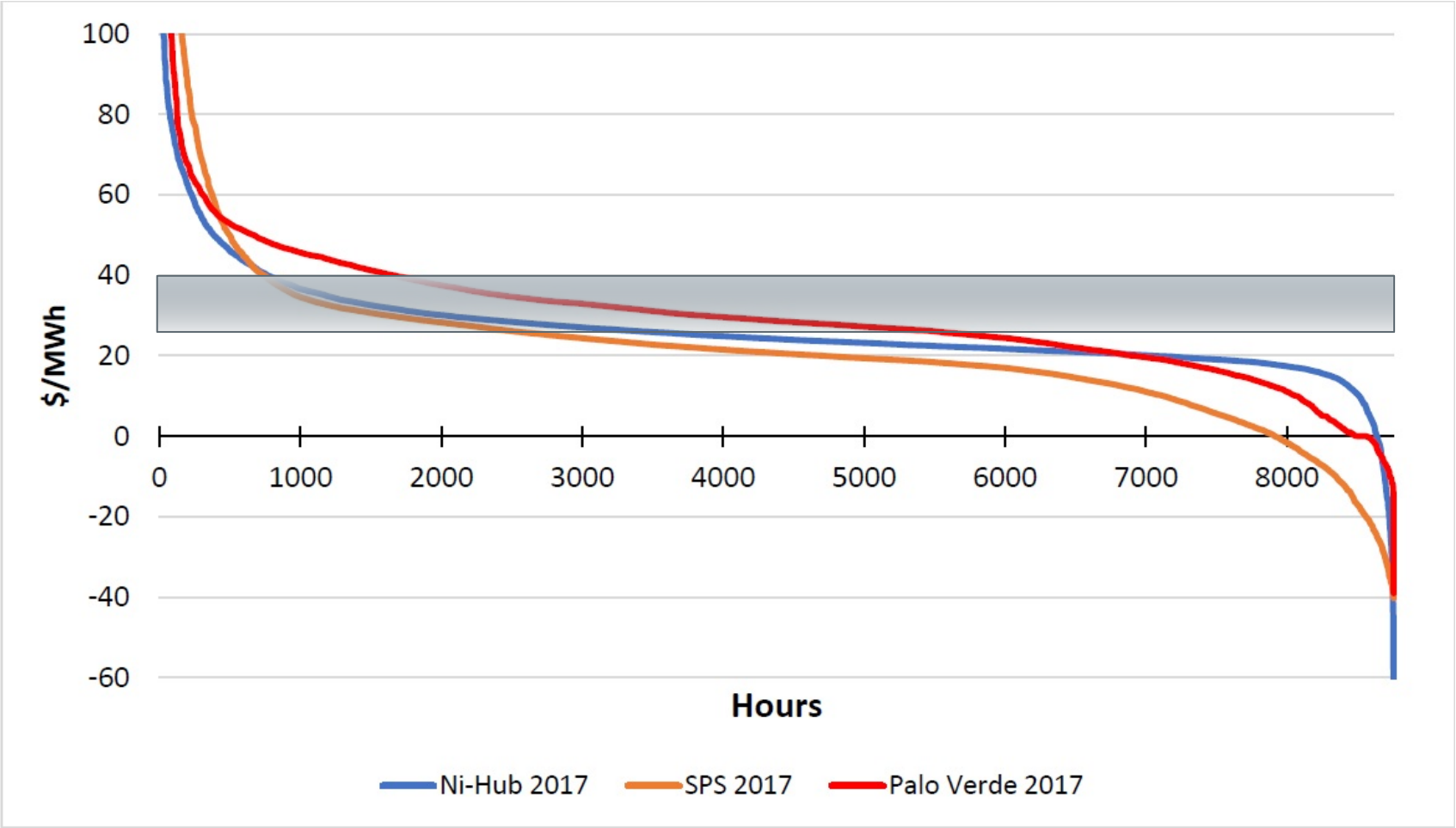
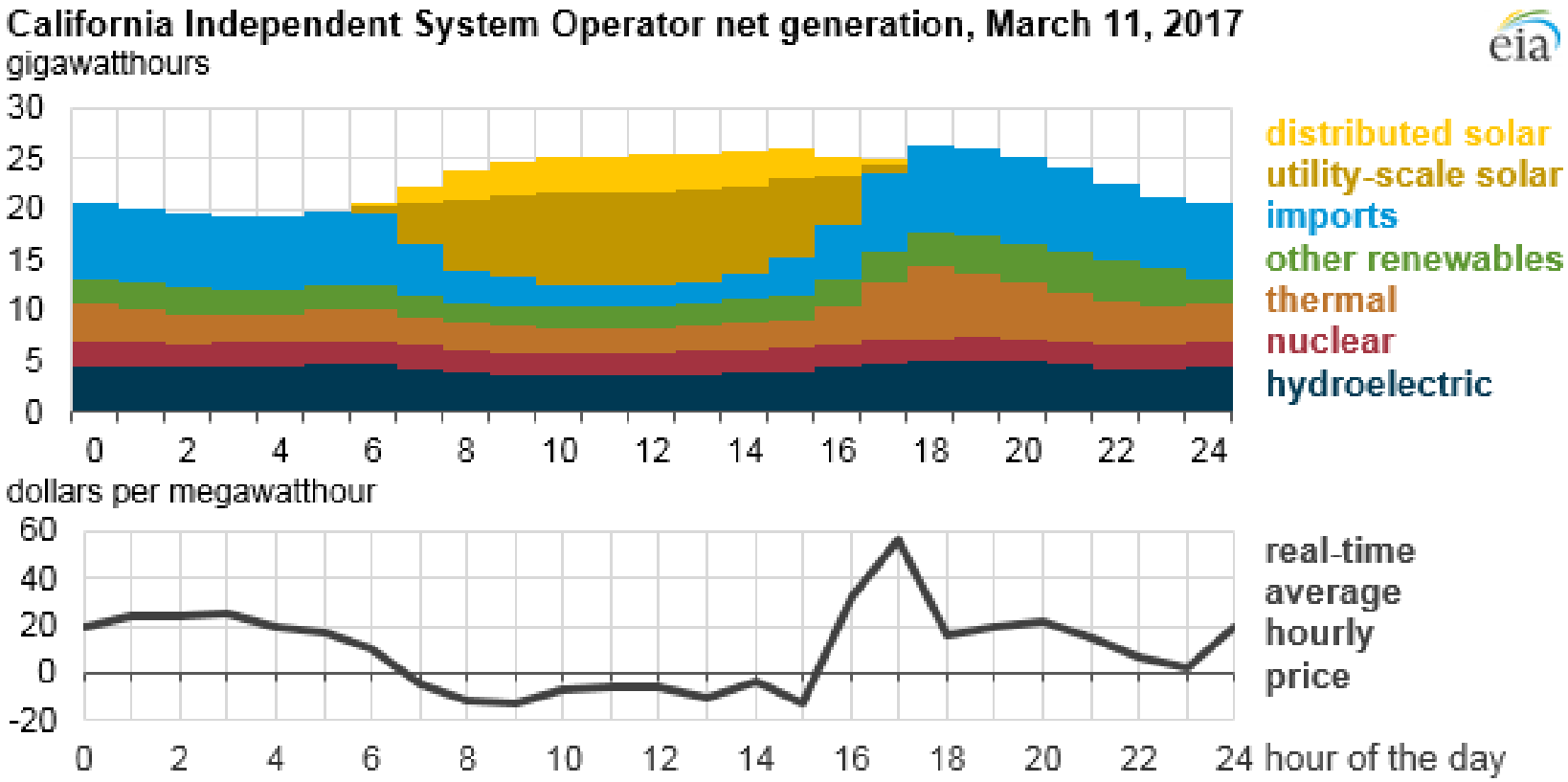


Figure created by NREL (Daniel Levie) based on publicly available price data

Some nuclear power plants may sell energy at a loss 35% or more of the hours in a year depending upon their technology, scale, location, and market.

With capital investment, new nuclear power plants are more challenged.

Electricity Sector Evolution



Source: **U.S. Energy Information Administration,** "Rising Solar Generation in California Coincides with Negative Wholesale Electricity Prices," EIA, Today in Energy, https://www.eia.gov/todayinenergy/detail.php?id=30692#tab4 (Apr. 7, 2017).

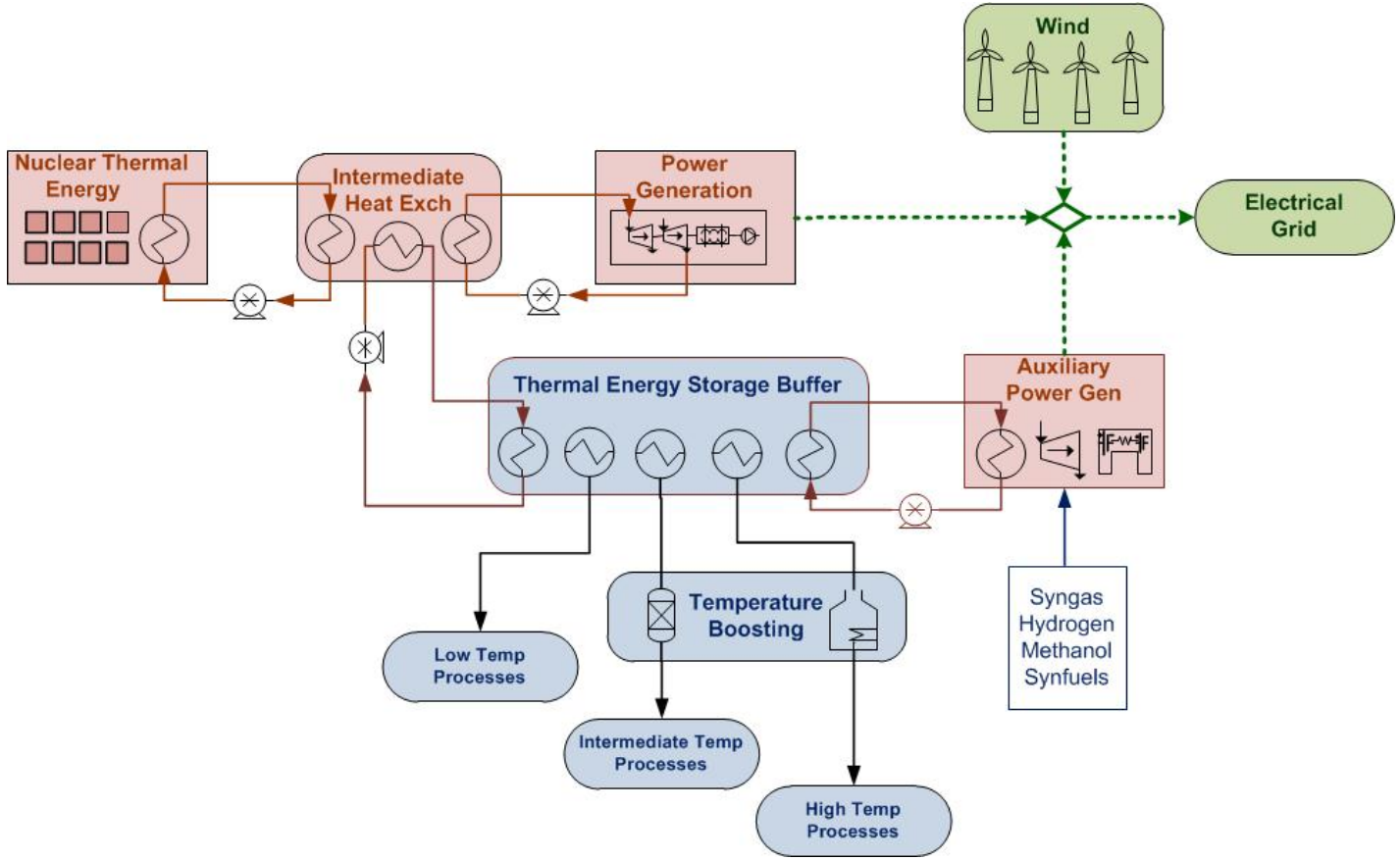
Electricity overgeneration causes hours with low or negative electricity prices.

Low price hours impact high capital – low operating cost technologies (nuclear and renewable) the most.

Possible Solution: Nuclear-Renewable Hybrid Energy Systems

Tightly-Coupled

Individual facilities which take **two or more energy resources as inputs** and **produce two or more products**, with at least one being an energy commodity such as electricity or a transportation fuel



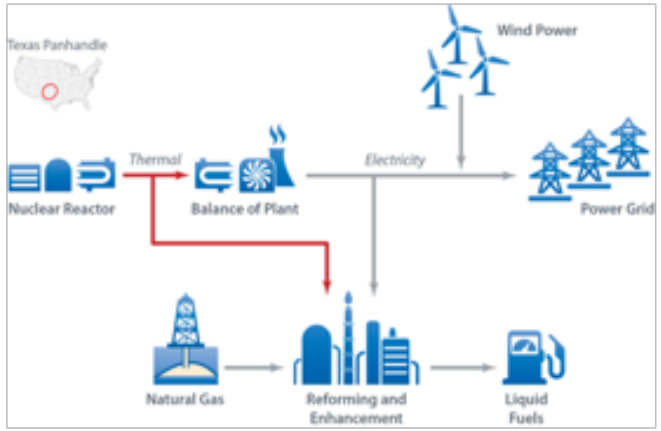
Source: RUTH, Mark F., ZINAMAN, Owen R., ANTKOWIAK, Mark, BOARDMAN, Richard D., CHERRY, Robert S., BAZILIAN, Morgan D. "Nuclear-renewable hybrid energy systems: Opportunities, interconnections, and needs," Energy Conversion and Management, Volume 78, February 2014, Pages 684-694, ISSN 0196-8904, http://dx.doi.org/10.1016/j.enconman.2013.11.030. (http://www.sciencedirect.com/science/article/pii/S0196890413007516)

Analysis Objective

- Financial (economic) analysis of N-R HES use cases
- Testing
  - Profitability
  - Profitability compared to natural gas alternatives
  - Competitiveness in grid resource adequacy markets
  - Potential for flexibility to improve profitability

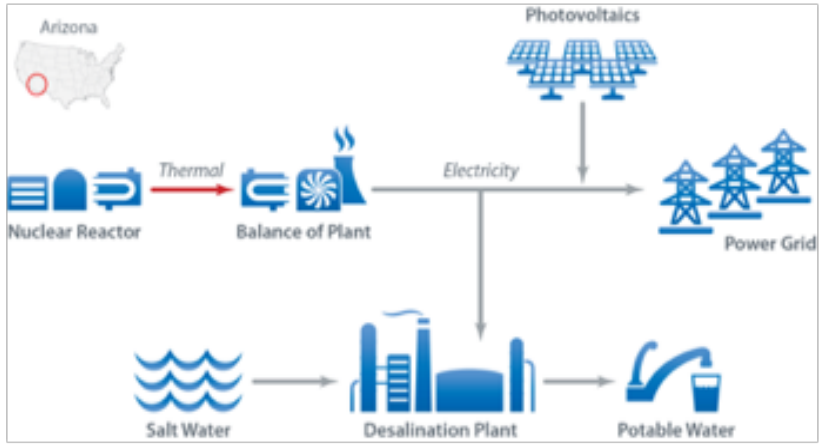
Use Cases Analyzed

Liquid Transportation Fuels



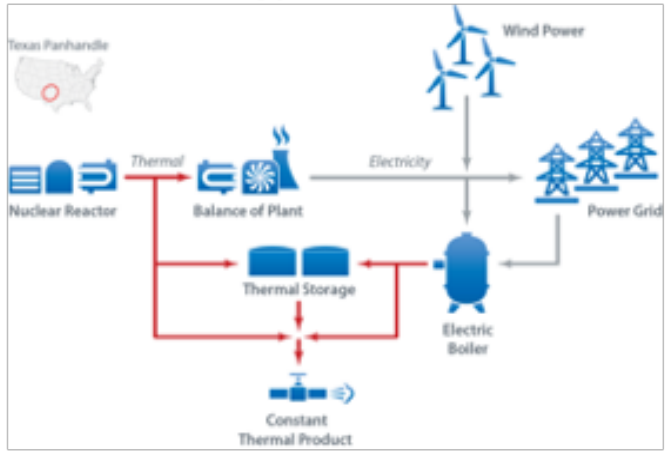
Thermal interconnection

Reverse Osmosis Desalination



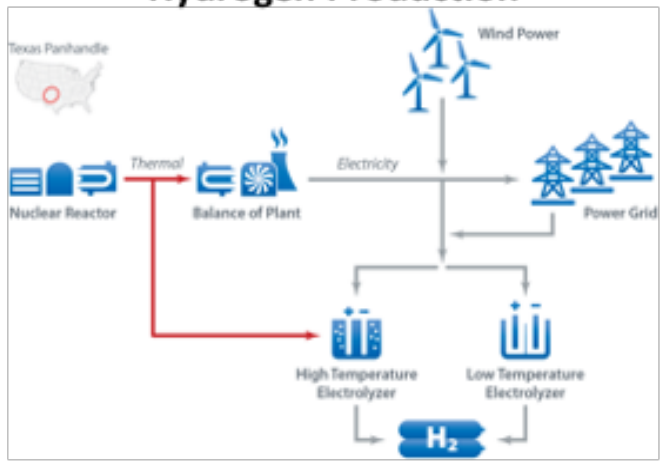
Electrical interconnection
No purchase of grid electricity

Thermal Energy in an Industrial Park



Thermal interconnection (primarily)
Possible purchase of grid electricity

Hydrogen Production



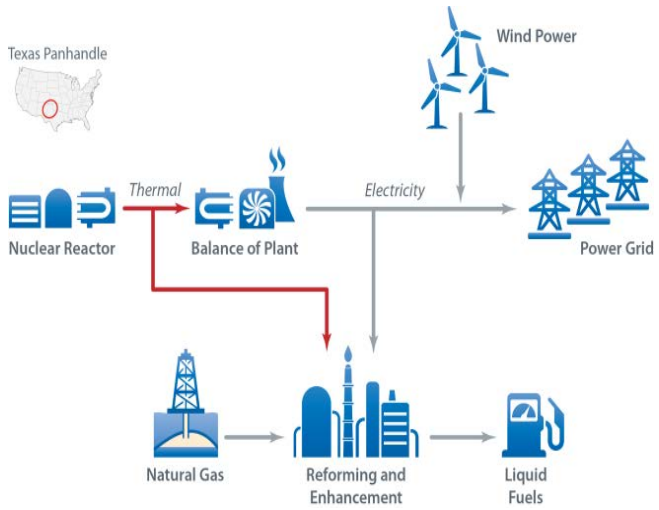
Electrical interconnection
Thermal interconnection for high temperature electrolysis.
Possible purchase of grid electricity

Ruth, Mark, Spitsen, Paul, Boardman, Richard, Bragg-Sitton, Richard "Opportunities and Challenges for Nuclear-Renewable Hybrid Energy Systems" Proceedings from IAEA Technical Meeting on Nuclear-Renewable Hybrid Energy Systems for Decarbonized Energy Production and Cogeneration. October 2018.

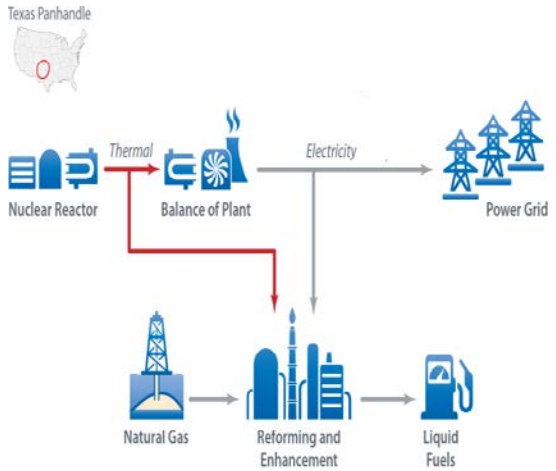
Analysis Methodology

Identify optimal configurations and internal dispatch under various product prices

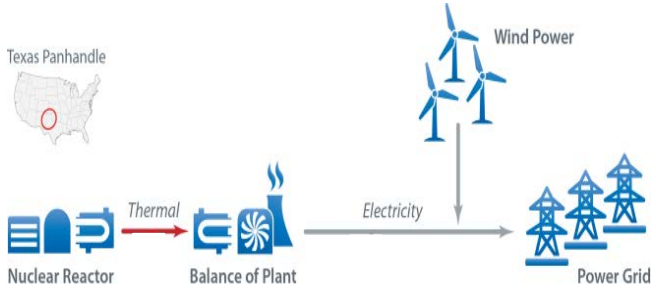
Full Configuration



Partial Configuration



Another Partial Configuration



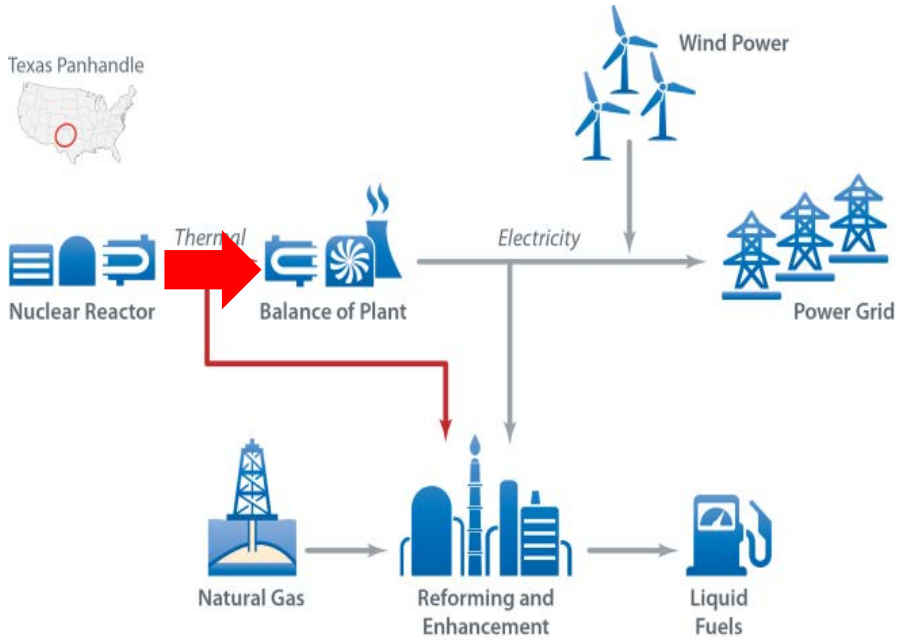
Other configurations: (1) nuclear-generated electricity only and (2) wind only

Source: Ruth, Mark, Cutler, Dylan, Flores-Espino, Francisco, Stark, Greg, Jenkin, Thomas, Simpkins, Travis, and Macknick, Jordan. *The Economic Potential of Two Nuclear-Renewable Hybrid Energy Systems*, 2016. NREL/TP-6A50-66073. http://www.nrel.gov/docs/fy16osti/66073.pdf

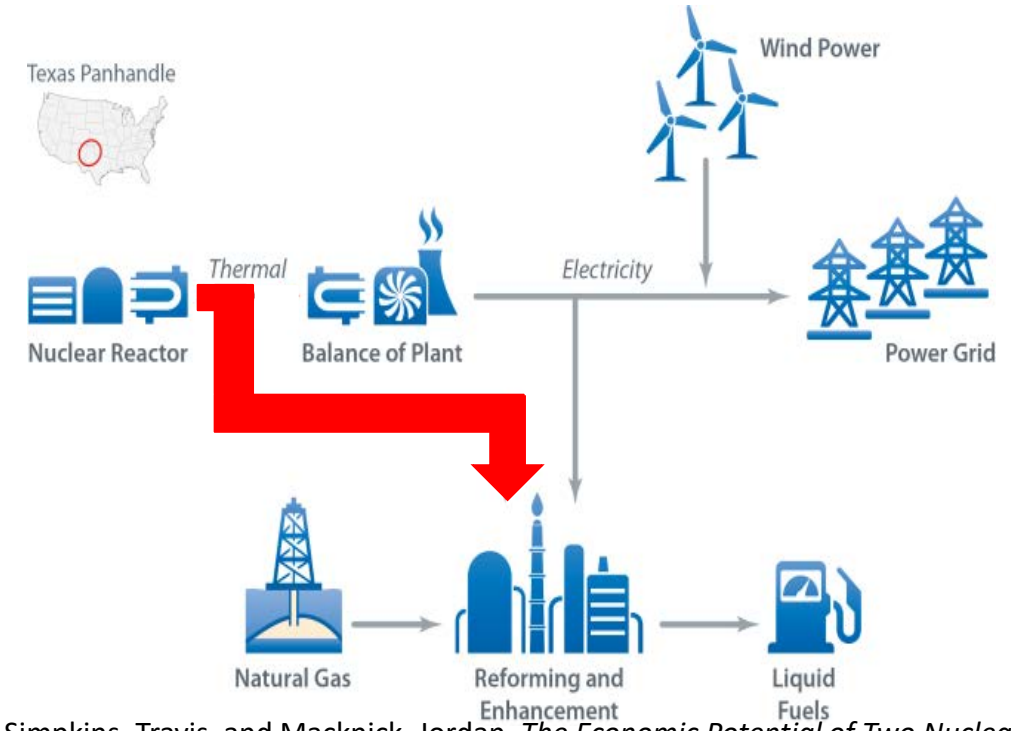
Analysis Methodology

Identify optimal configurations and
internal dispatch under various product prices

One Dispatch Option

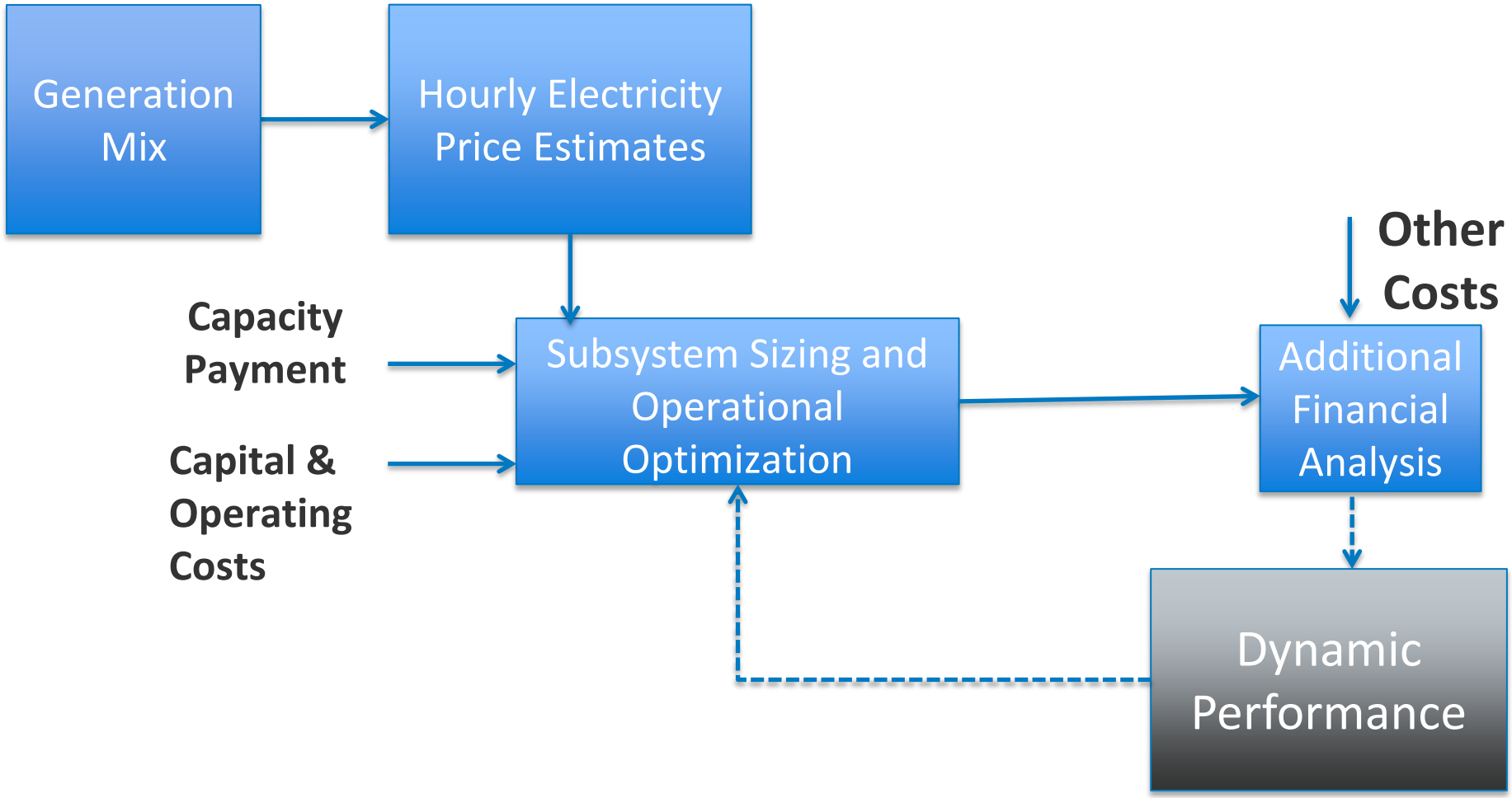


Second Dispatch Option



Adapted from Ruth, Mark, Cutler, Dylan, Flores-Espino, Francisco, Stark, Greg, Jenkin, Thomas, Simpkins, Travis, and Macknick, Jordan. *The Economic Potential of Two Nuclear-Renewable Hybrid Energy Systems*, 2016. NREL/TP-6A50-66073. http://www.nrel.gov/docs/fy16osti/66073.pdf

Analysis Methodology



Adapted from Ruth, Mark, Cutler, Dylan, Flores-Espino, Francisco, Stark, Greg, Jenkin, Thomas, Simpkins, Travis, and Macknick, Jordan. *The Economic Potential of Two Nuclear-Renewable Hybrid Energy Systems*, 2016. NREL/TP-6A50-66073. http://www.nrel.gov/docs/fy16osti/66073.pdf

Analysis Methodology

Developed from Standard Scenarios: Used the 2036 mix for the RPS80 scenario as the baseline

Generation Mix

Hourly Electricity Price Estimates

Estimated as marginal operational costs using PLEXOS unit commitment modeling

Other Costs

Capacity Payment

Capital & Operating Costs

Based on historical costs and competition from natural gas combustion turbines: $50/kW-yr

Required to provide power during 50 highest load hours in the year

From Annual Technology Baseline and INL estimates

Subsystem Sizing and Operational Optimization

Used REopt to identify optimal configurations and internal dispatch

Maximum sizes for all subsystems set to 50 MWe equivalent

Additional Financial Analysis

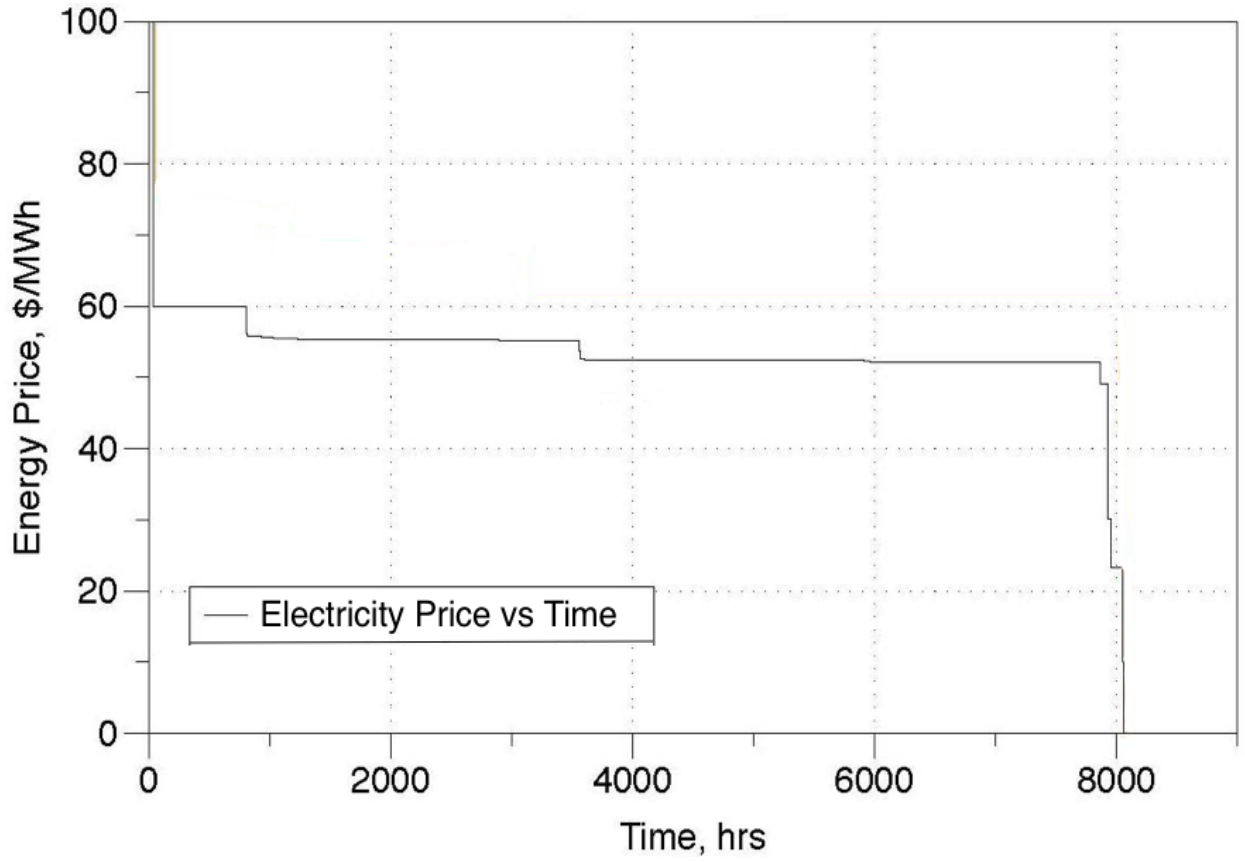
10% after tax IRR on 100% equity financing. 25 year analysis life. 35% tax rate. 3% inflation rate.

Electricity Prices

Developed and used generation mixes that cause volatile electricity prices

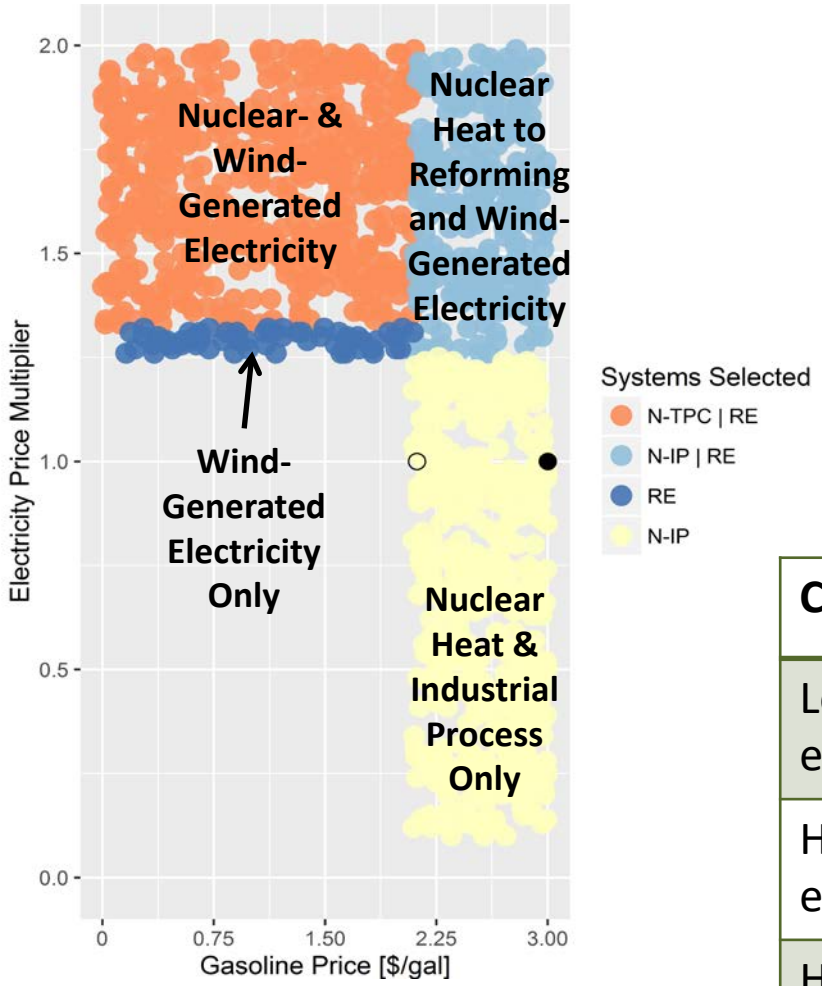
Price Set	Primary	Arizona	Volatile
Wind generation percentage	21%	11%	8.6%
PV generation percentage	20%	22%	37%
Hours at $0/MWh annually	704	700	2,246

Energy Price Duration Curve for Texas Use Cases

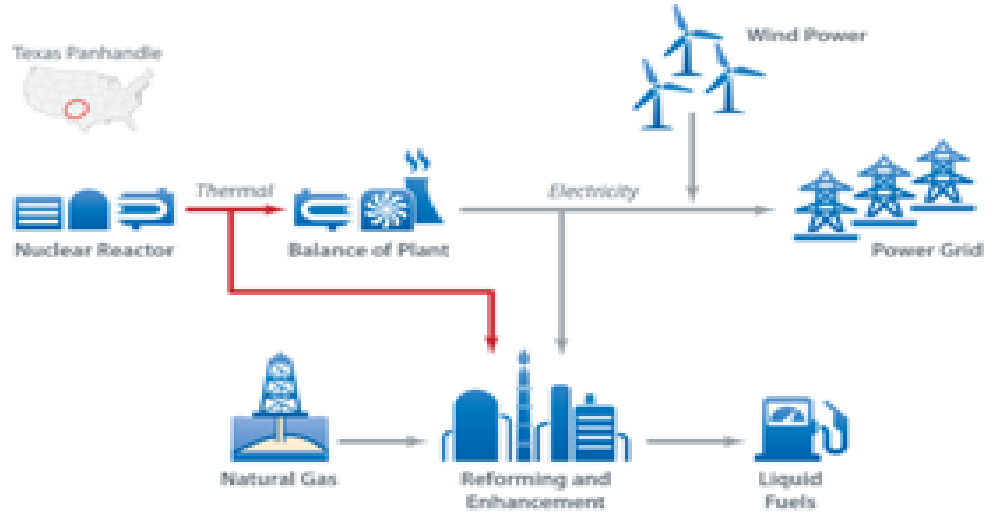


Ruth, Mark, Spitsen, Paul, Boardman, Richard, Bragg-Sitton, Richard "Opportunities and Challenges for Nuclear-Renewable Hybrid Energy Systems" Proceedings from IAEA Technical Meeting on Nuclear-Renewable Hybrid Energy Systems for Decarbonized Energy Production and Cogeneration. October 2018.

Optimal Configurations Liquid Fuels Use Case



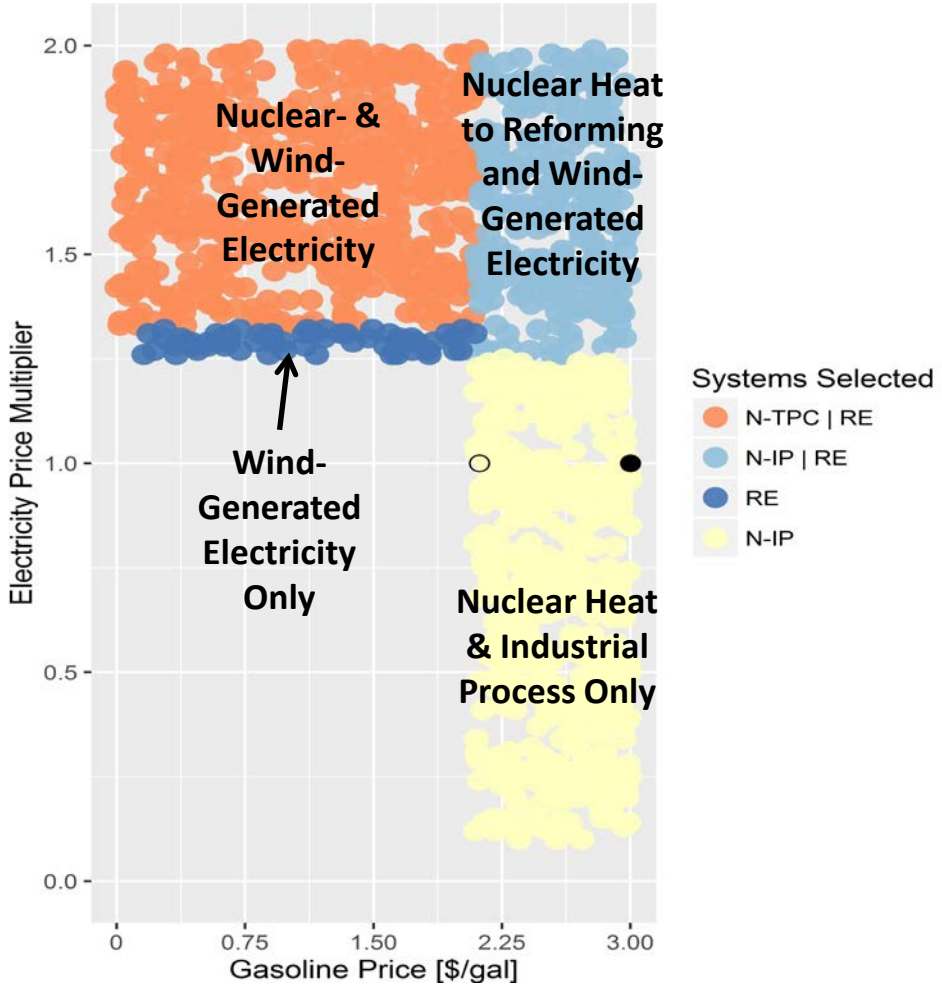
N-TPC: Nuclear reactor and thermal
N-IP: Nuclear reactor and industrial process
RE: Renewable electricity generation



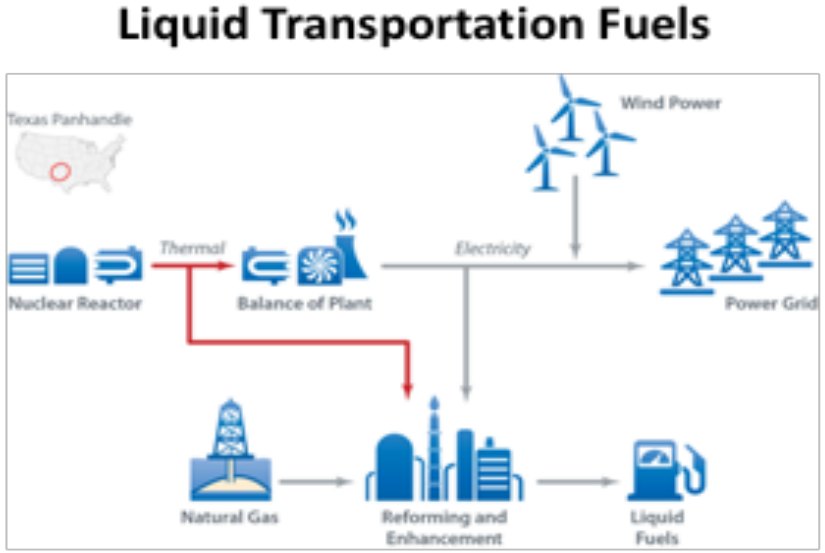
Conditions	Optimal Configurations
Low gasoline prices & high electricity price multiplier	Both nuclear- & wind-generated electricity
High gasoline prices & lower electricity price multiplier	Nuclear heat and industrial process only
High gasoline prices & high electricity price multiplier	Nuclear heat and industrial process with wind generation

Source: Ruth, Mark, Cutler, Dylan, Flores-Espino, Francisco, Stark, Greg, Jenkin, Thomas, Simpkins, Travis, and Macknick, Jordan. *The Economic Potential of Two Nuclear-Renewable Hybrid Energy Systems*, 2016. NREL/TP-6A50-66073. http://www.nrel.gov/docs/fy16osti/66073.pdf

Subsystems are Optimally Included if Independently Profitable



N-TPC: Nuclear reactor and thermal
N-IP: Nuclear reactor and industrial process
RE: Renewable electricity generation



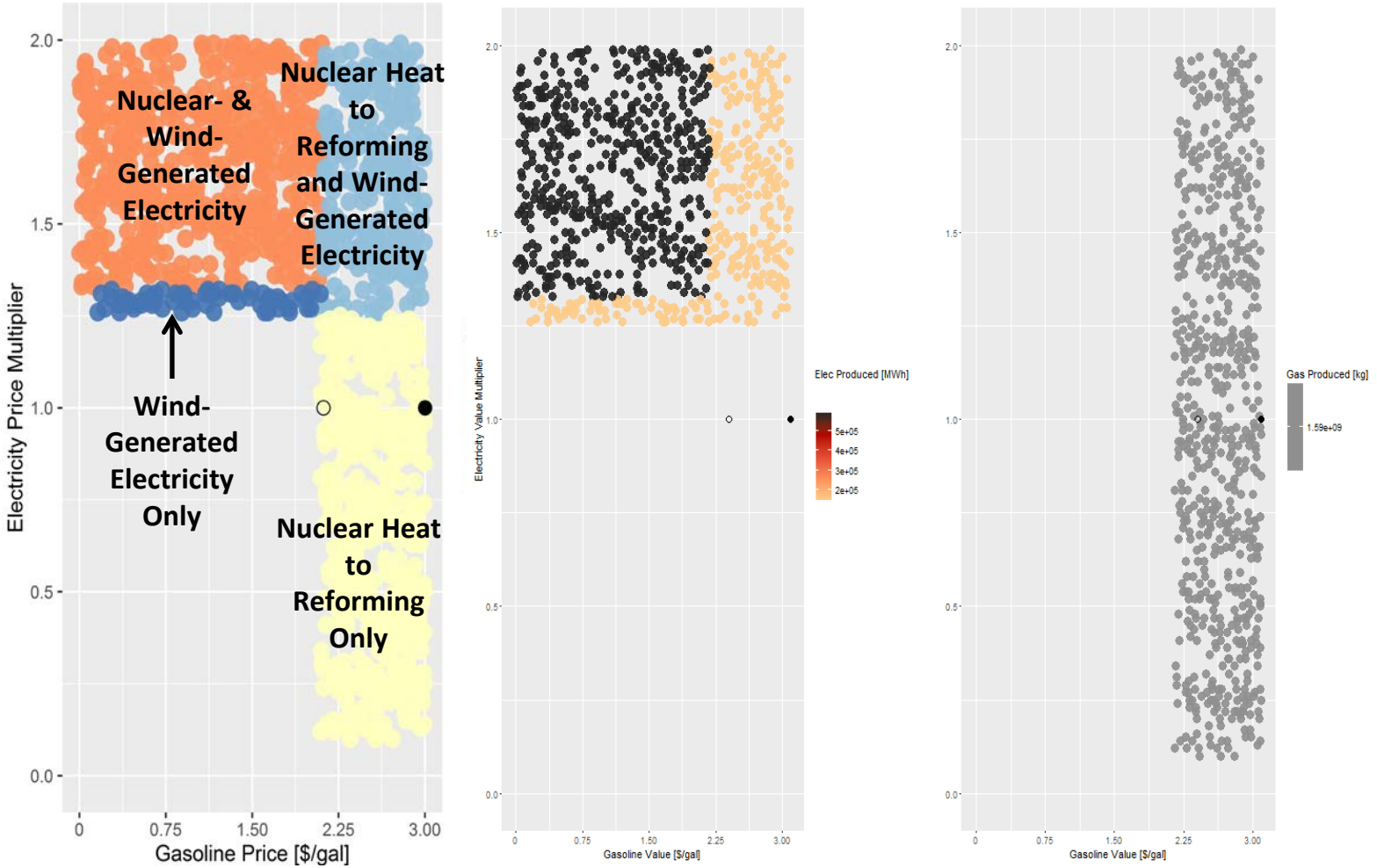
Conclusion #1:
Under our analytical method and most of our assumptions, the primary driver for whether a subsystem is included in the optimal configuration is whether it would be profitable independently

Major Caveats:

- Negligible grid connection costs
- No value for inertia or resilience

Source: Ruth, Mark, Cutler, Dylan, Flores-Espino, Francisco, Stark, Greg, Jenkin, Thomas, Simpkins, Travis, and Macknick, Jordan. *The Economic Potential of Two Nuclear-Renewable Hybrid Energy Systems*, 2016. NREL/TP-6A50-66073. http://www.nrel.gov/docs/fy16osti/66073.pdf

Optimal Operation: Maximize Hours that Industrial Process Operates



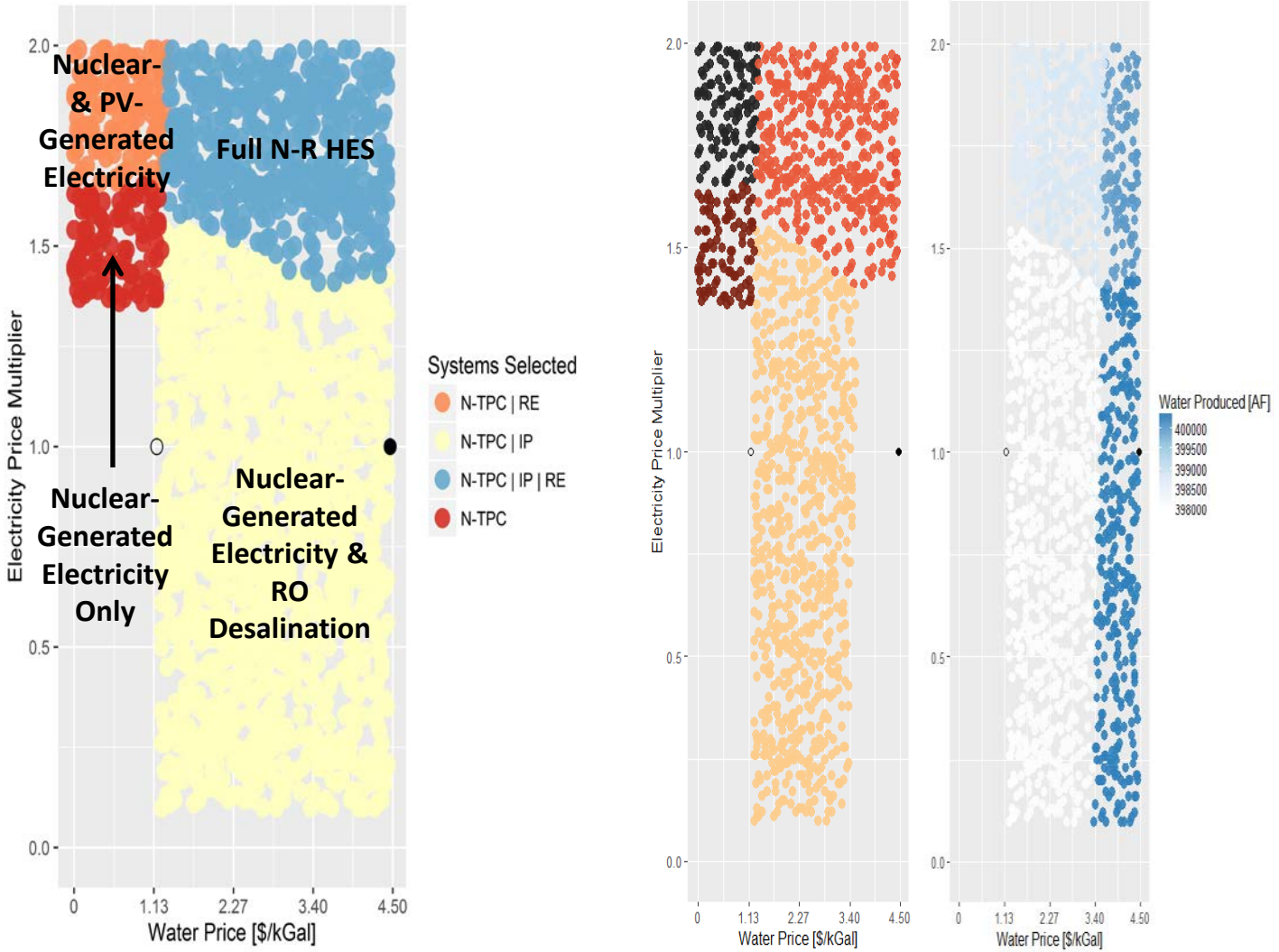
N-TPC: Nuclear reactor and thermal
N-IP: Nuclear reactor and industrial process
RE: Renewable electricity generation

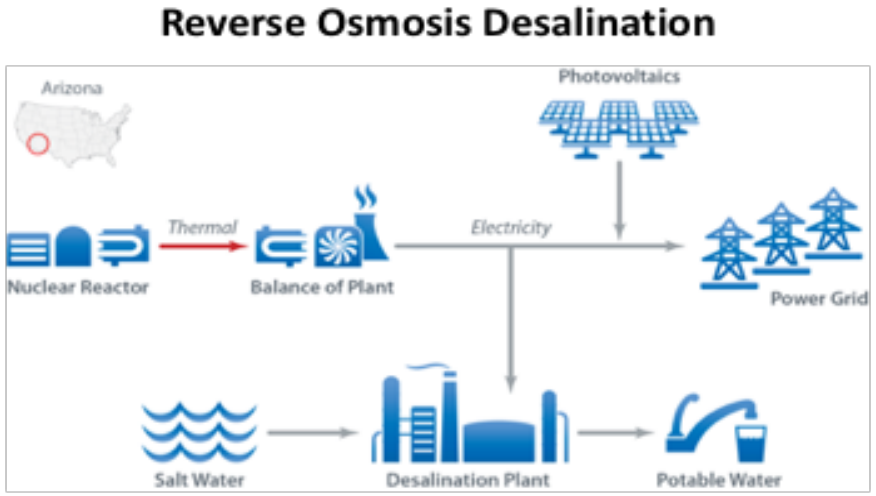
Conclusion #2:
Industrial processes usually maximize profitability by operating the maximum number of hours possible in a year

In other words:
Our electricity price assumptions are insufficiently volatile for arbitrage (even with high renewables & capacity payments)

Source: Ruth, Mark, Cutler, Dylan, Flores-Espino, Francisco, Stark, Greg, Jenkin, Thomas, Simpkins, Travis, and Macknick, Jordan. *The Economic Potential of Two Nuclear-Renewable Hybrid Energy Systems*, 2016. NREL/TP-6A50-66073. http://www.nrel.gov/docs/fy16osti/66073.pdf

But Lower Cost Equipment Partially Overcomes Second Conclusion



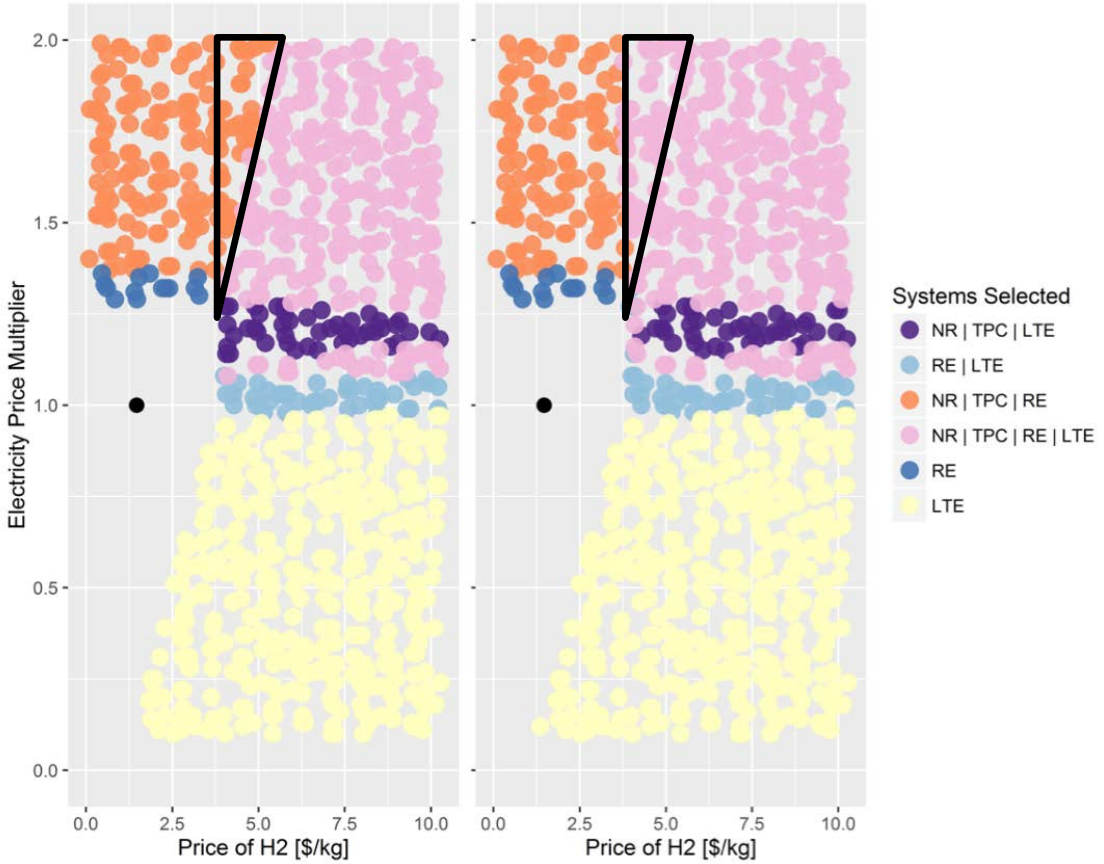


Exception to #2:
Systems with lower hourly income required from the industrial process may optimally reduce the industrial product to receive a capacity payment (white & lighter blue regions in water production graph)

Source: Ruth, Mark, Cutler, Dylan, Flores-Espino, Francisco, Stark, Greg, Jenkin, Thomas, Simpkins, Travis, and Macknick, Jordan. *The Economic Potential of Two Nuclear-Renewable Hybrid Energy Systems*, 2016. NREL/TP-6A50-66073. http://www.nrel.gov/docs/fy16osti/66073.pdf

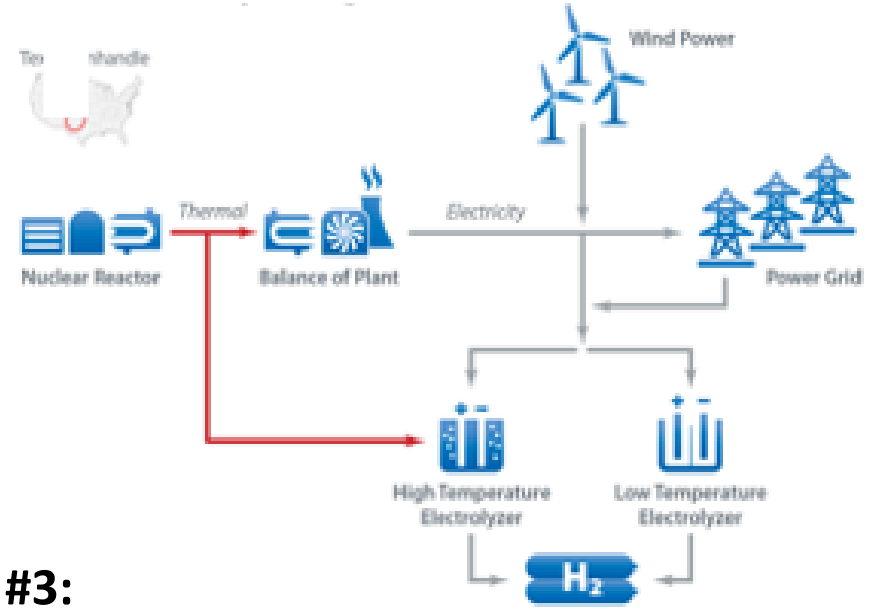
Flexibility Benefits N-R HESs with Lower Capital Cost Industrial Processes

Capital Investment: $616/kW $154/kW



LTE: low temperature electrolysis subsystem
NR: nuclear reactor
RE: renewable electricity generation (wind power plant)
TPC: thermal power cycle

Low Temperature Electrolysis (LTE)

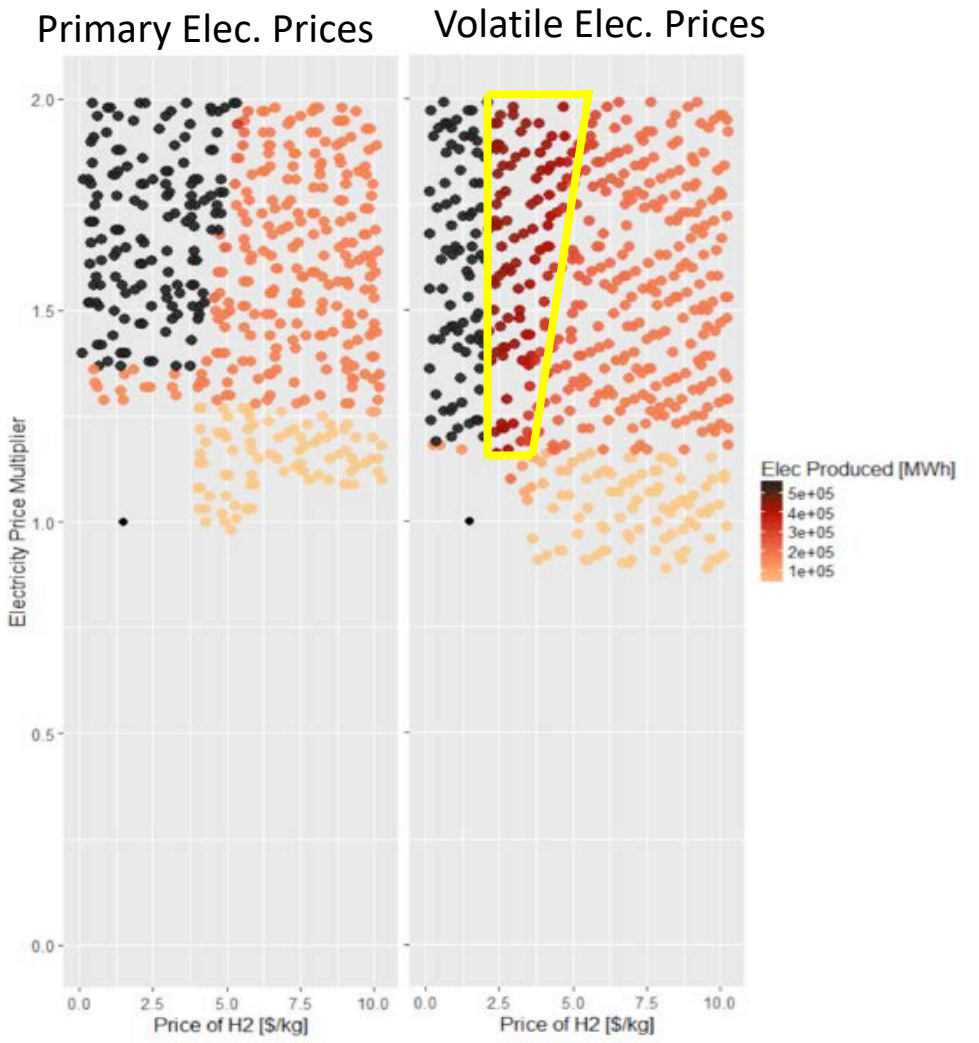


Conclusion #3:

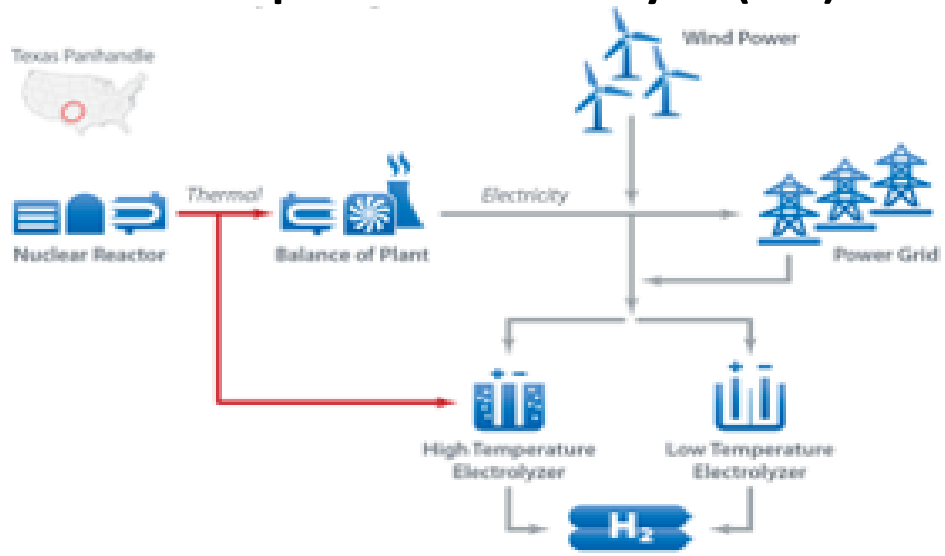
- Lower capital cost industrial processes are more likely to utilize their flexibility to switch between electricity and the industrial product more often than their higher capital cost configurations
- This flexibility increases the number of profitable situations

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

Flexibility Benefits N-R HESs when Electricity Prices are High & Volatile



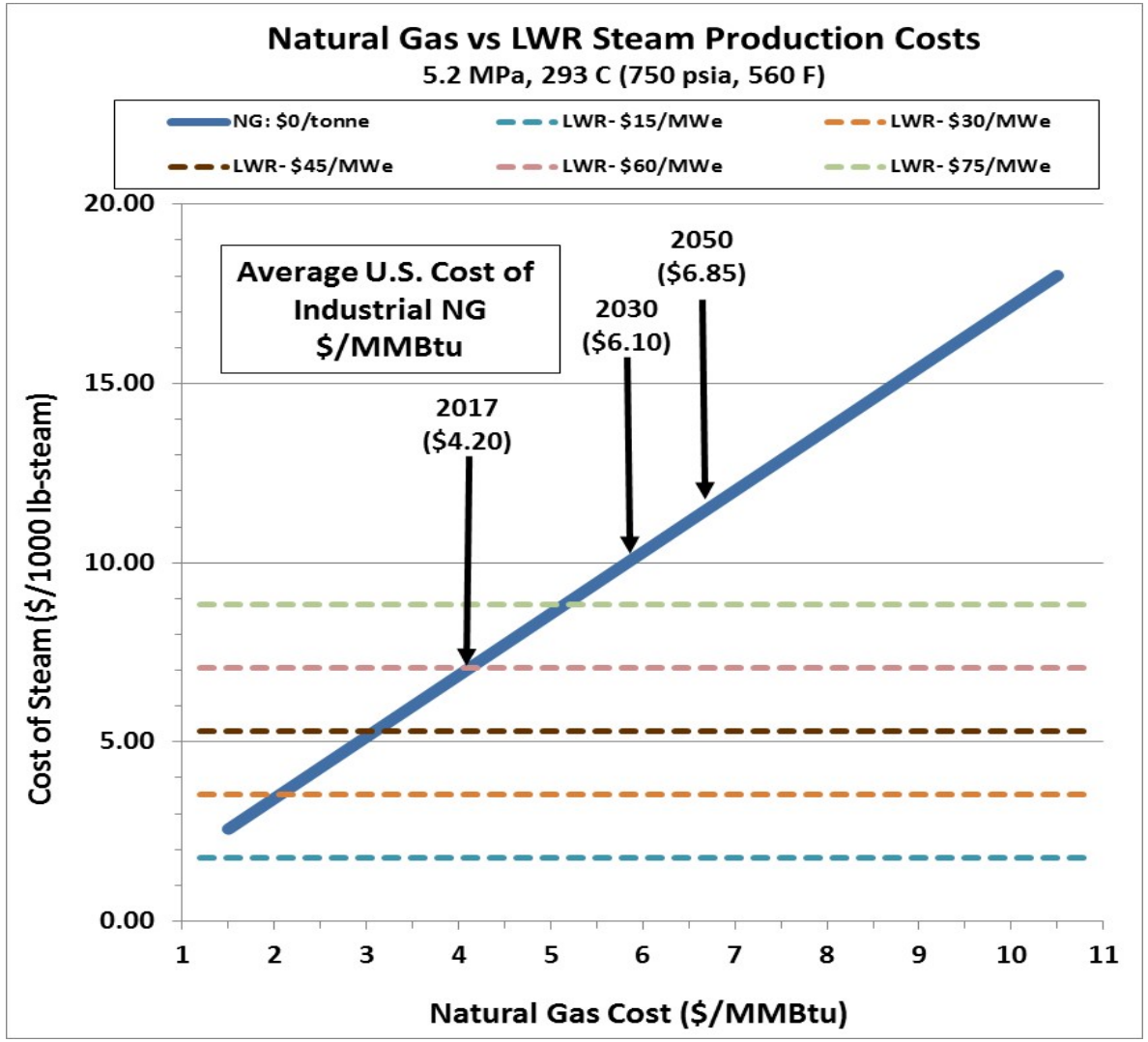
Low Temperature Electrolysis (LTE)



- N-R HES can produce electricity when price is high and industrial product when electricity price is low as shown in the yellow polygon
- High and volatile energy prices necessary to realize the benefits of arbitrage

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

Thermal Energy May Be an Opportunity for Nuclear Energy



Conclusion #4:
Nuclear reactors may be competitive selling thermal energy

Providing a thermal energy market exists and they can access that market

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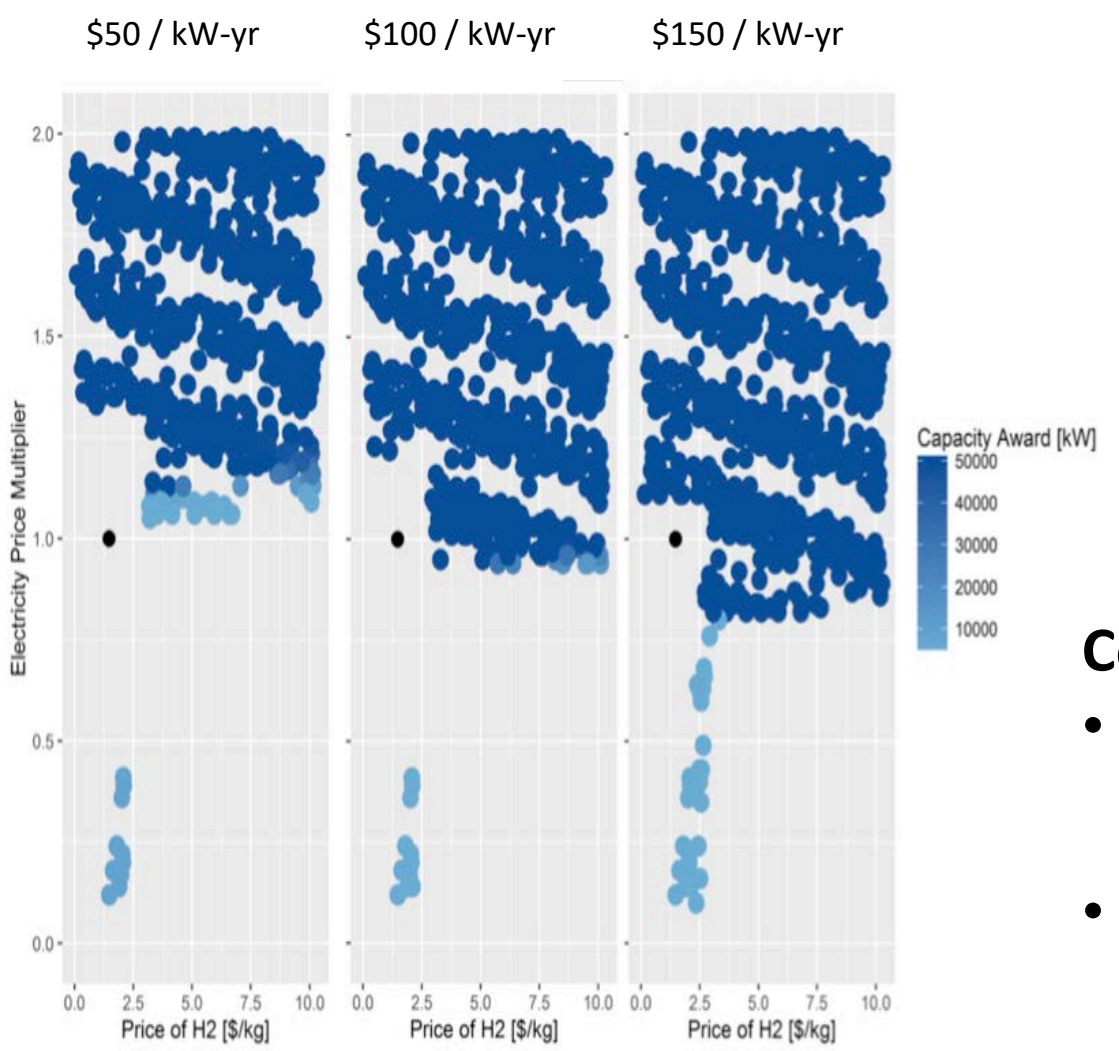
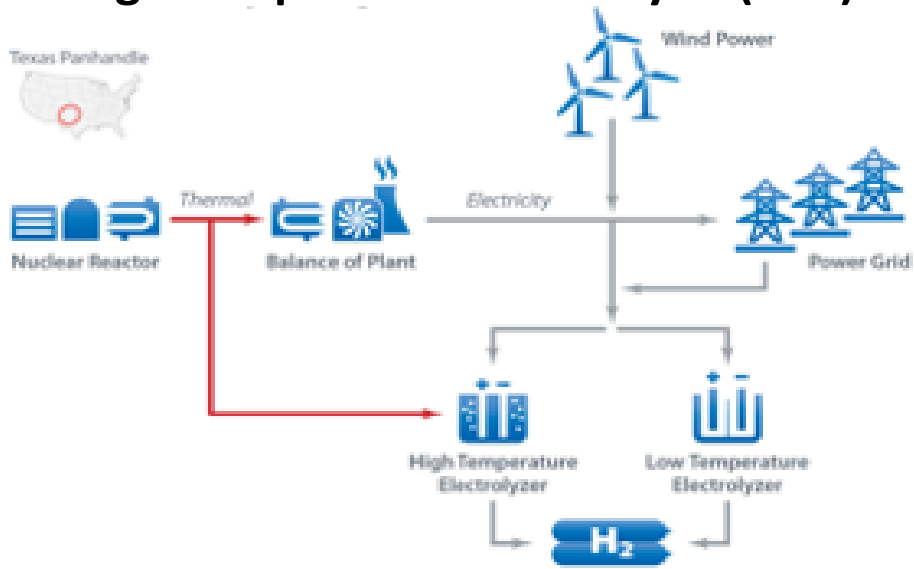
High Temperature Electrolysis N-R HES: Impact of Capacity Payments



High Temperature Electrolysis (HTE)



Conclusion #5:

- Higher capacity payments lead to more optimal configurations that provide grid support
- But a sufficient industrial product 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

Challenges and Opportunities - Reiterated

1. Under our analytical method and most of our assumptions, the primary driver for whether a subsystem is included in the optimal configuration is whether it would be profitable independently
2. Industrial processes usually maximize profitability by operating the maximum number of hours possible in a year
3. Lower capital cost industrial processes are more likely to utilize their flexibility to switch between electricity and the industrial product more often than their higher capital cost configuration. This flexibility increases the number of profitable situations
4. Nuclear reactors may be competitive selling thermal energy providing a thermal energy market exists and they can access that market
5. Higher capacity payments lead to more optimal configurations that provide grid support but a sufficient industrial product price is still critical

Thank you!

NREL/PR-6A50-81121

mark.ruth@nrel.gov

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