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Opportunities and Challenges for Nuclear-Renewable Hybrid Energy Systems

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IAEA Technical Meeting on Nuclear-Renewable Hybrid Energy Systems for Decarbonized Energy Production and Cogeneration

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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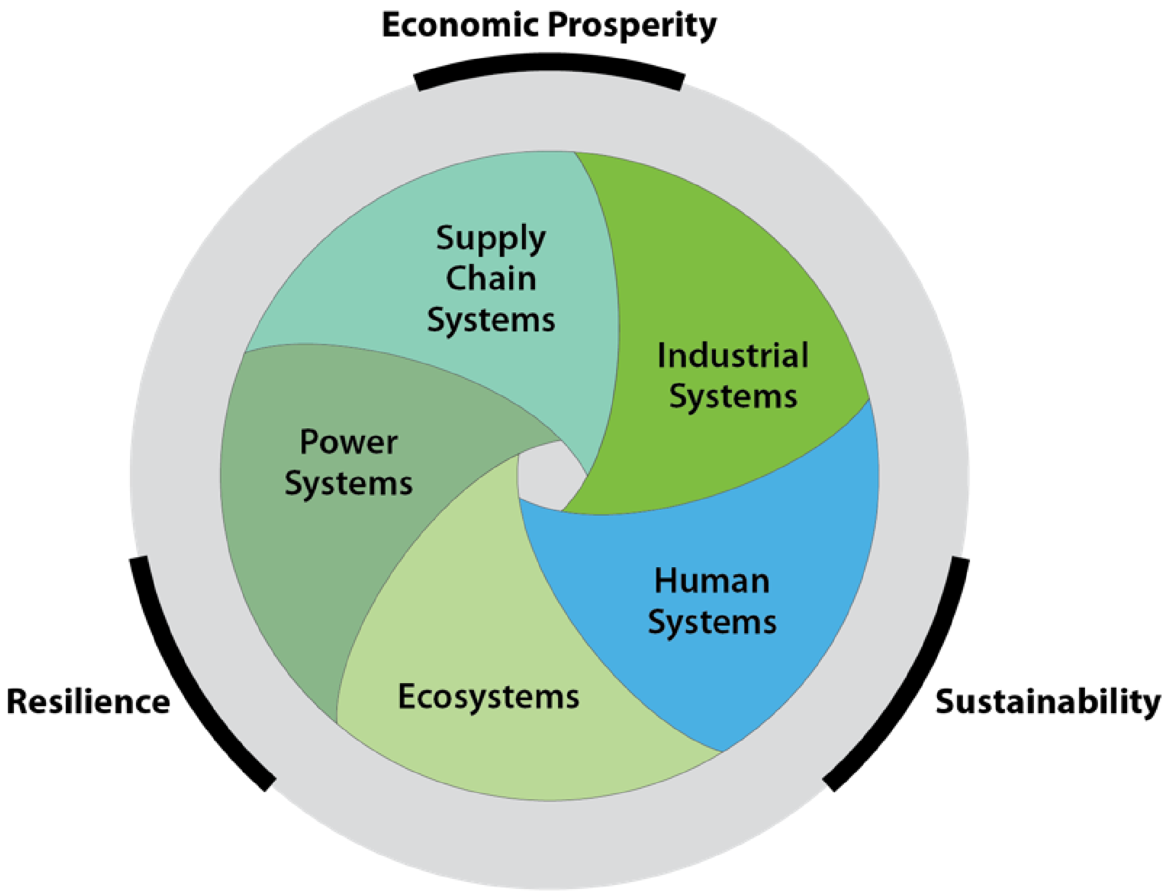
JISEA

Joint Institute for Strategic Energy Analysis

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



Founding Members

NREL NATIONAL RENEWABLE ENERGY LABORATORY · COLORADO SCHOOL OF MINES · Colorado State University · MIT Massachusetts Institute of Technology · STANFORD UNIVERSITY · University of Colorado Boulder

NICE Future Initiative Began at CEM9 2018

NICE Future
Nuclear Innovation: Clean Energy Future

CLEAN ENERGY MINISTERIAL
Accelerating the Global Clean Energy Transition

Vision

NICE Future envisions nuclear power as an important energy option for clean, reliable, and resilient baseload electricity and non-electric applications and includes advanced and innovative designs and applications.

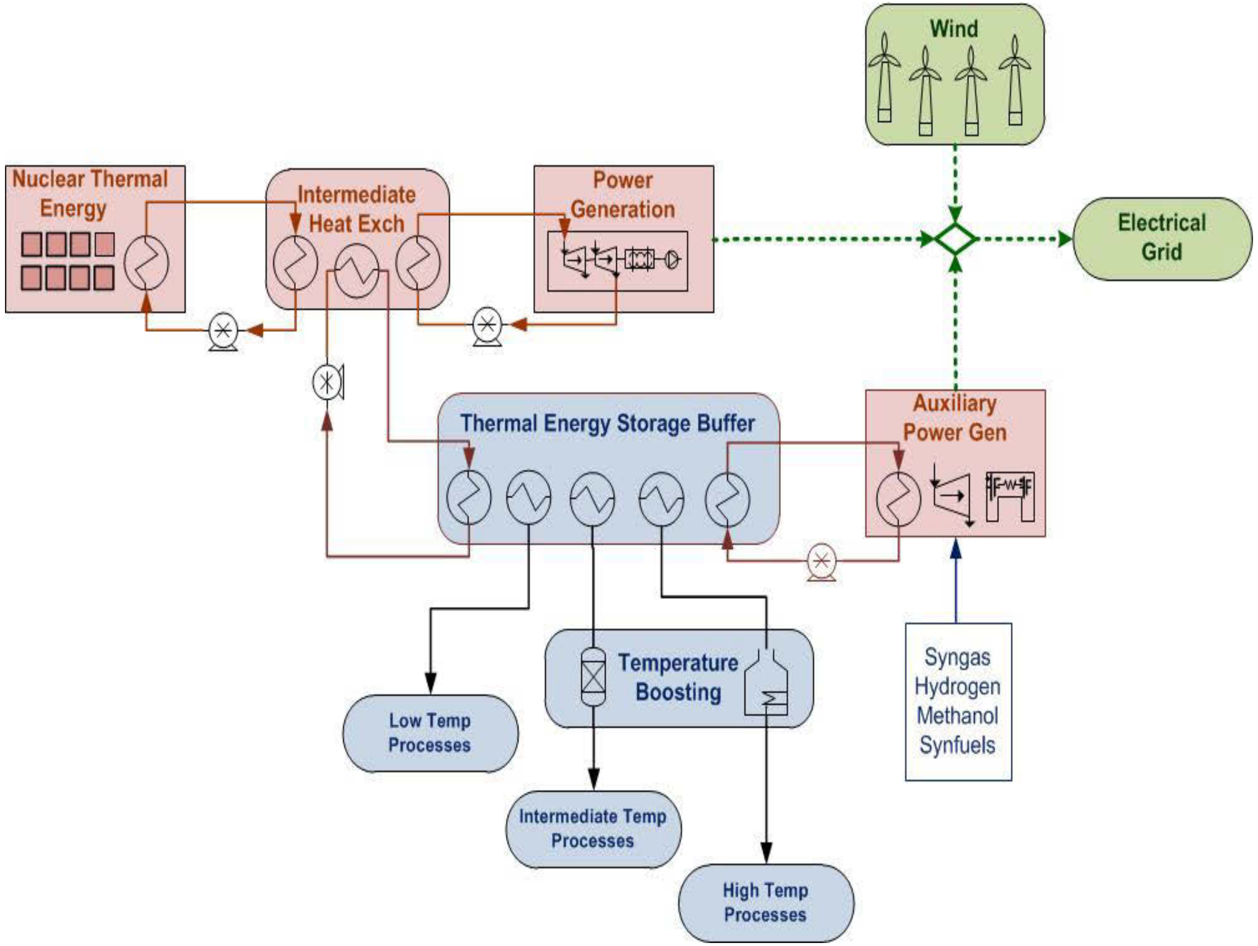
Areas of Work:

1. Evaluations of innovative systems, technology, storage, uses
2. Engagement
3. Economics
4. Communicating nuclear energy's role in clean energy systems

Working Definition of an N-R HES

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)

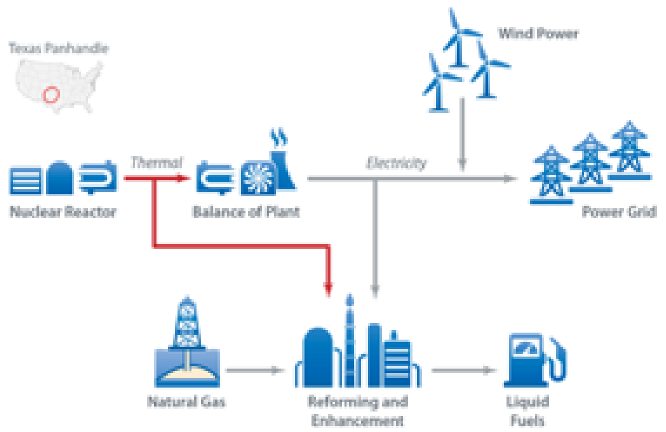
Analysis Objective

- 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

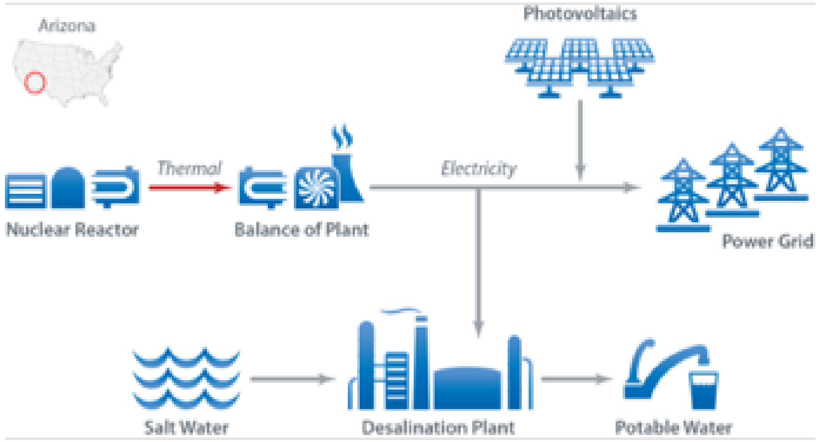
Use Cases Analyzed

Thermal interconnection

Liquid Transportation Fuels



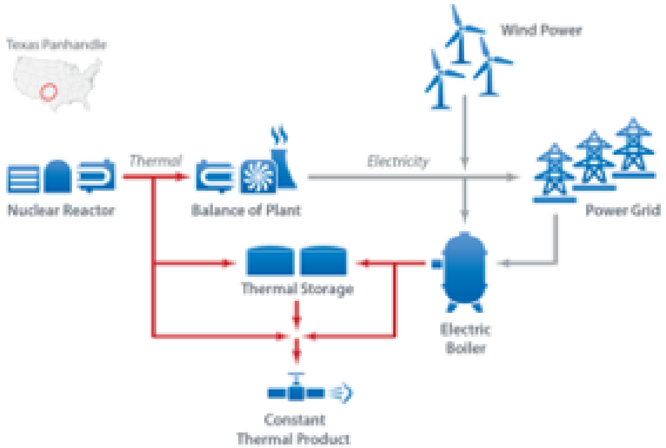
Reverse Osmosis Desalination



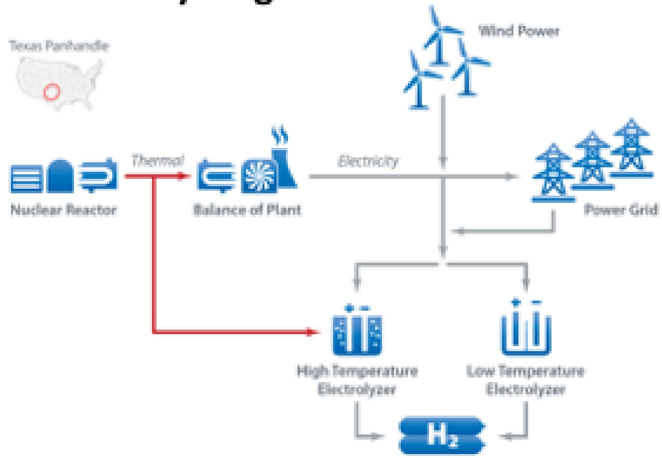
Electrical interconnection
No purchase of grid electricity

Thermal interconnection (primarily)
Possible purchase of grid electricity

Thermal Energy in an Industrial Park



Hydrogen Production



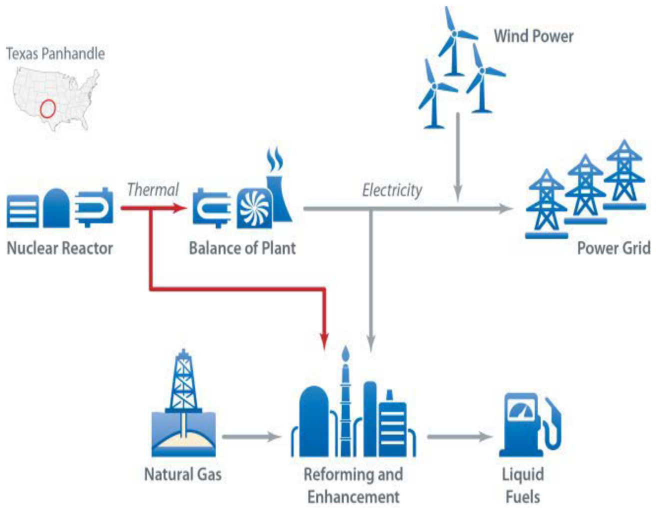
Electrical interconnection
Thermal interconnection for high temperature electrolysis.
Possible purchase of grid electricity

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.

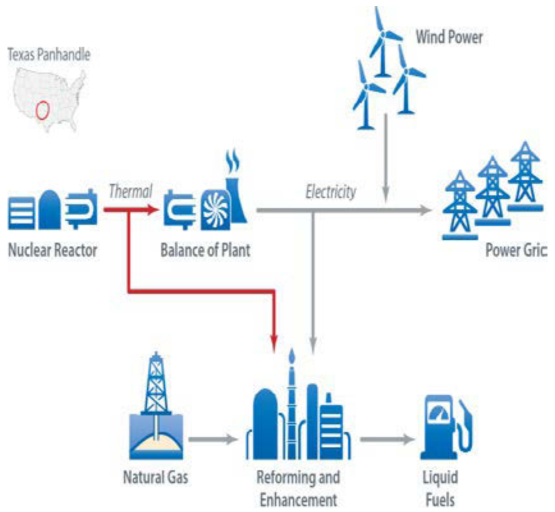
Analysis Methodology

Identify optimal configurations and internal dispatch under various product prices

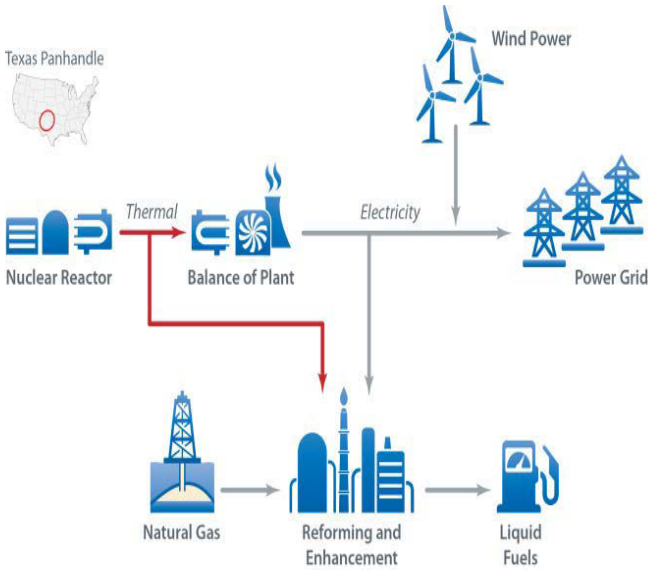
Full Configuration



Partial Configuration



Another Partial Configuration



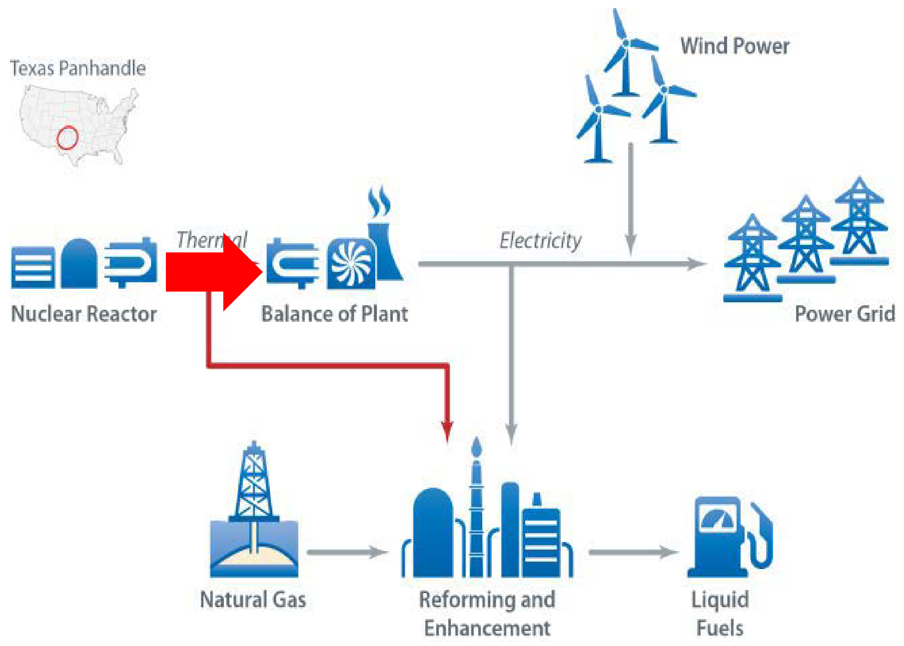
Other configurations: (1) nuclear-generated electricity only and (2) wind only

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

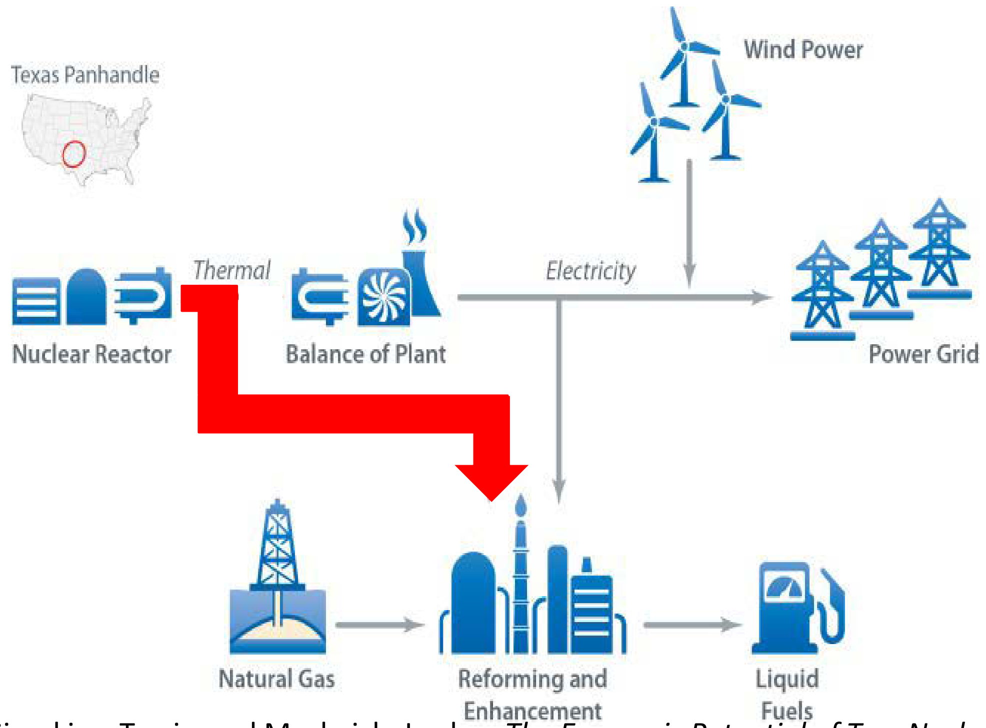
Analysis Methodology

Identify optimal configurations and
internal dispatch under various product prices

One Dispatch Option

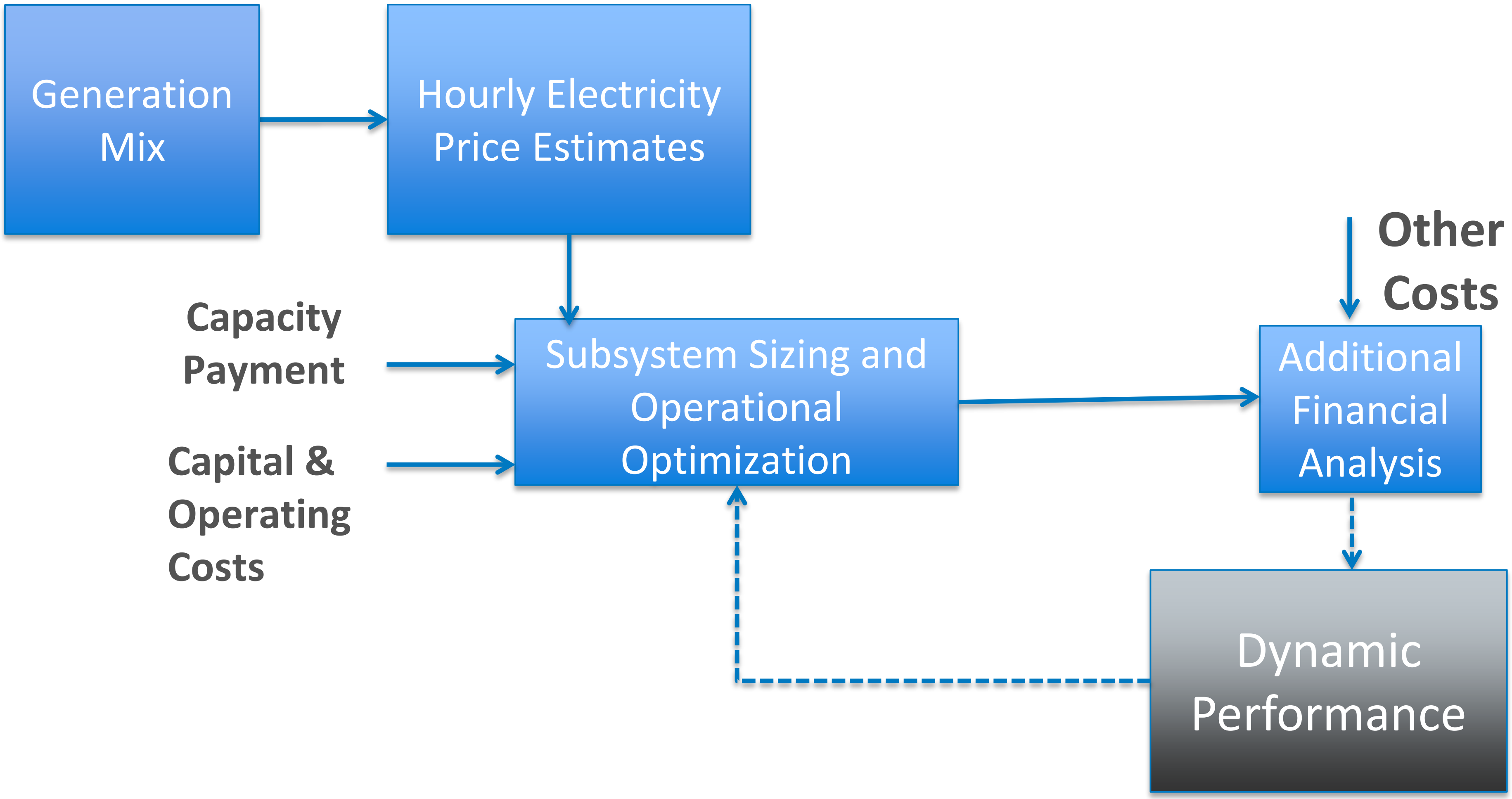


Second Dispatch Option



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



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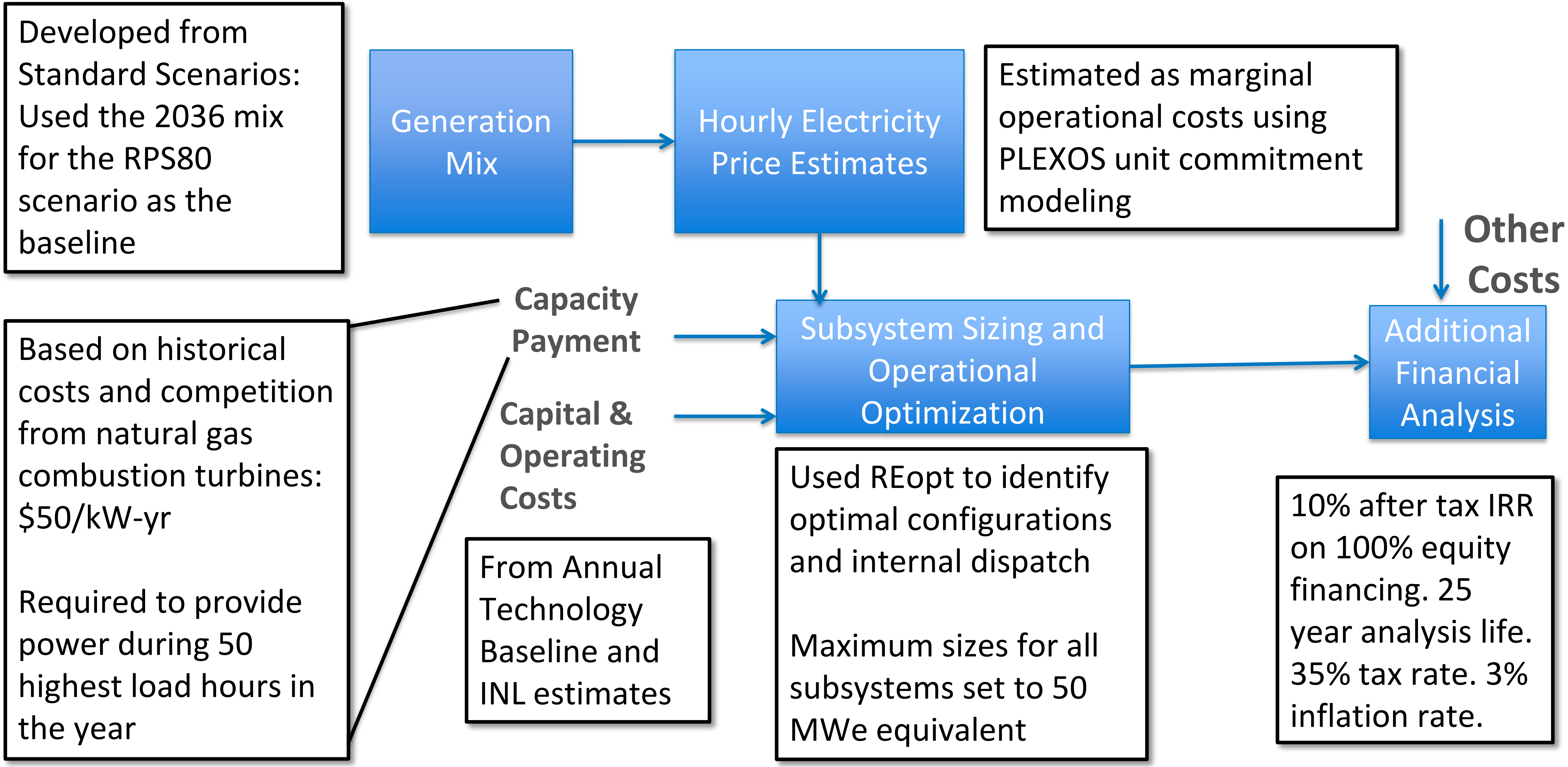
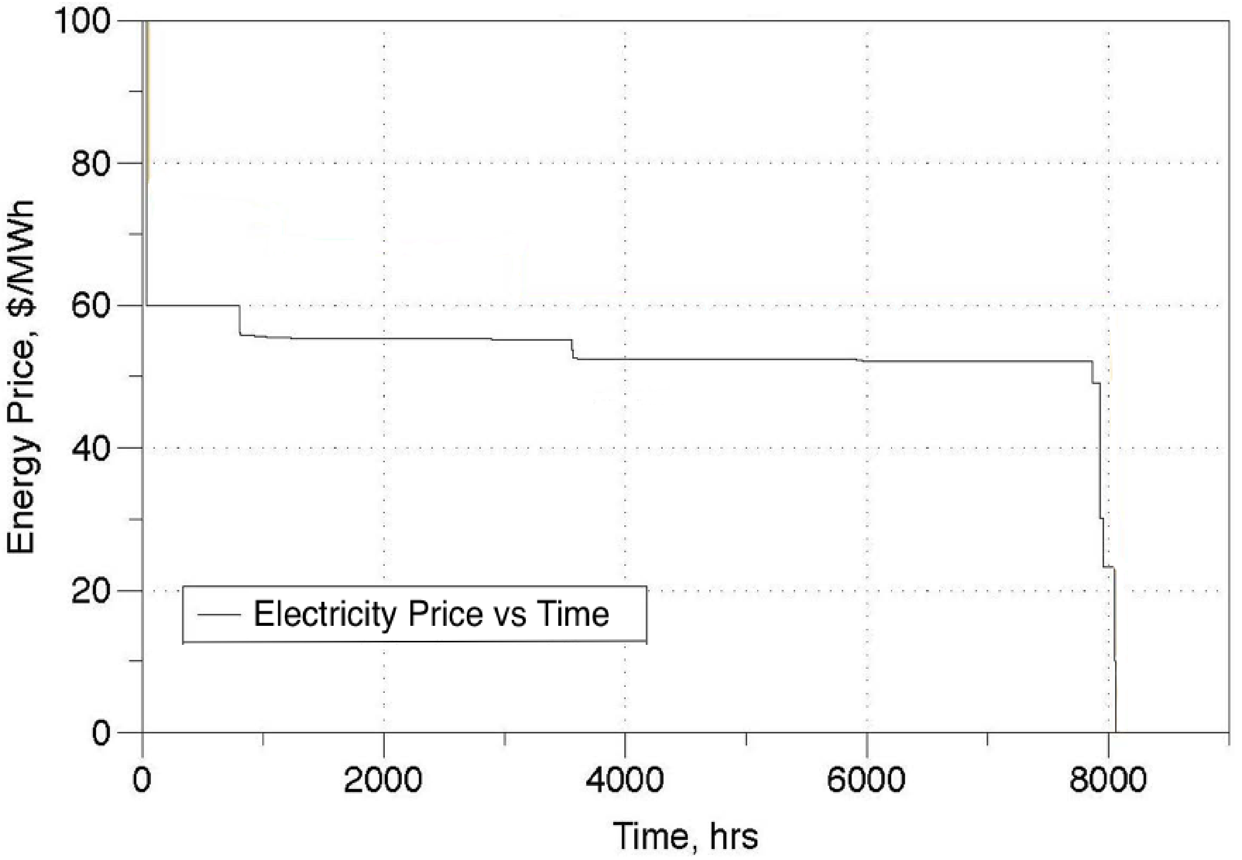


Electricity Prices

Developed and used generation mixes that cause volatile electricity prices

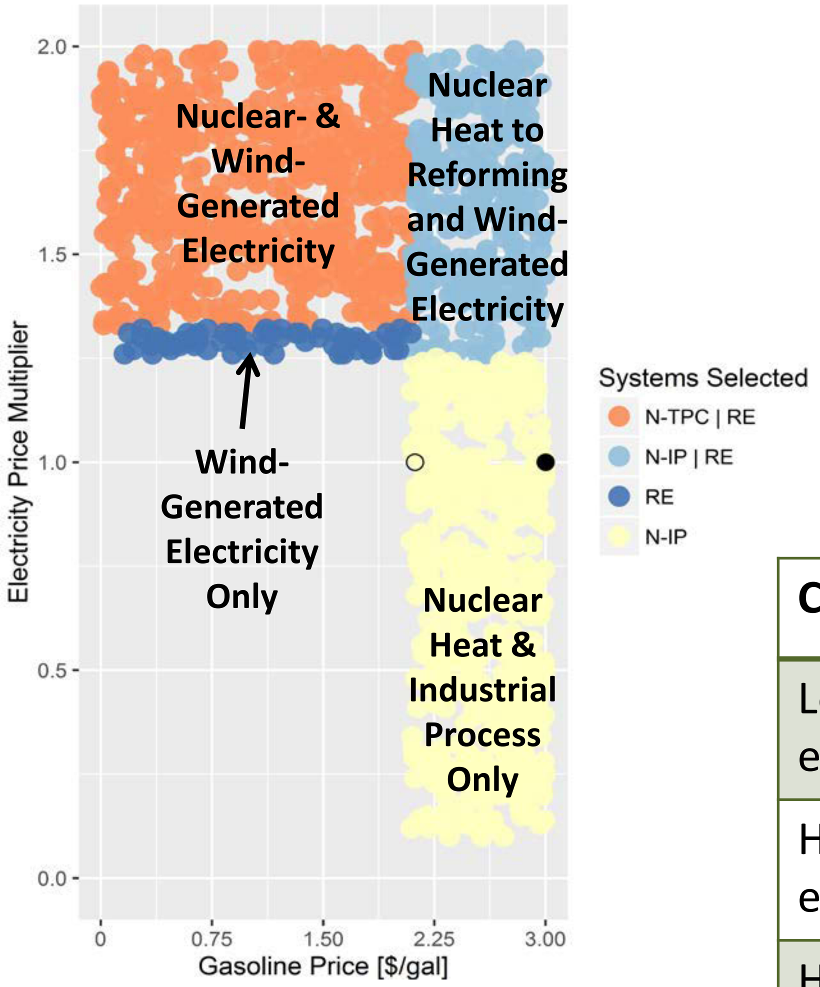
Price Set	Primary	Arizona	Volatile
Wind generation percentage	21%	11%	8.6%
PV generation percentage	20%	22%	37%
Hours at $0/MWh annually	704	700	2,246

Energy Price Duration Curve for Texas Use Cases

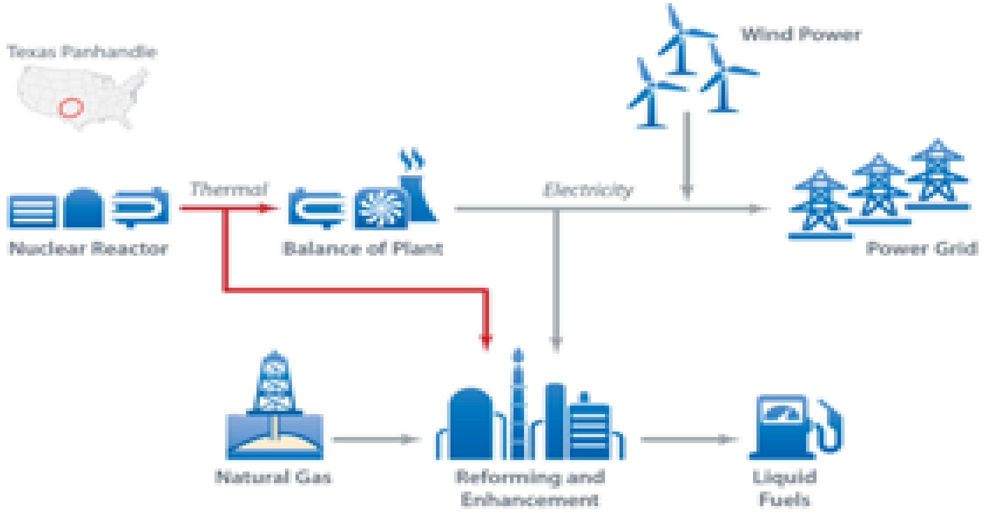


Ruth, Mark, Spitsen, Paul, Boardman, Richard, Bragg-Sitton, Richard "Opportunities and Challenges for Nuclear-Renewable Hybrid Energy Systems" Proceedings from IAEA Technical Meeting on Nuclear-Renewable Hybrid Energy Systems for Decarbonized Energy Production and Cogeneration. October 2018.

Optimal Configurations Liquid Fuels Use Case



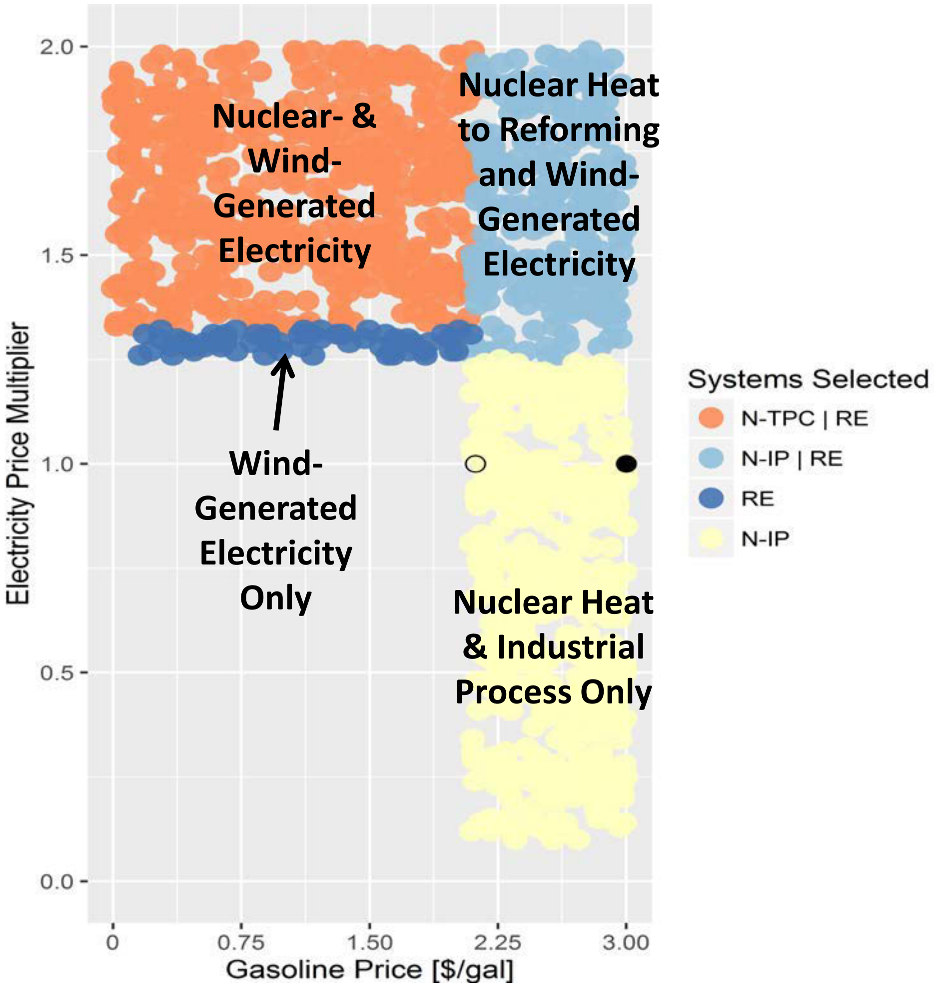
N-TPC: Nuclear reactor and thermal
N-IP: Nuclear reactor and industrial process
RE: Renewable electricity generation



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



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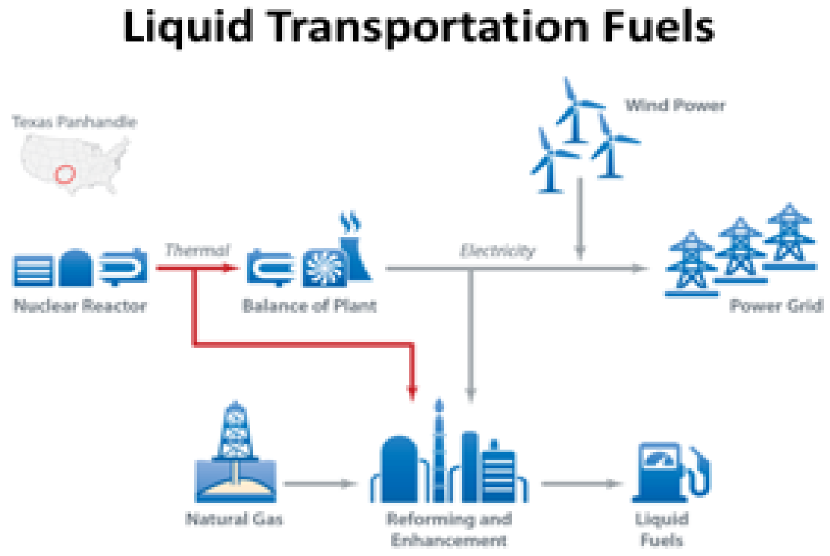


Conclusion #1:

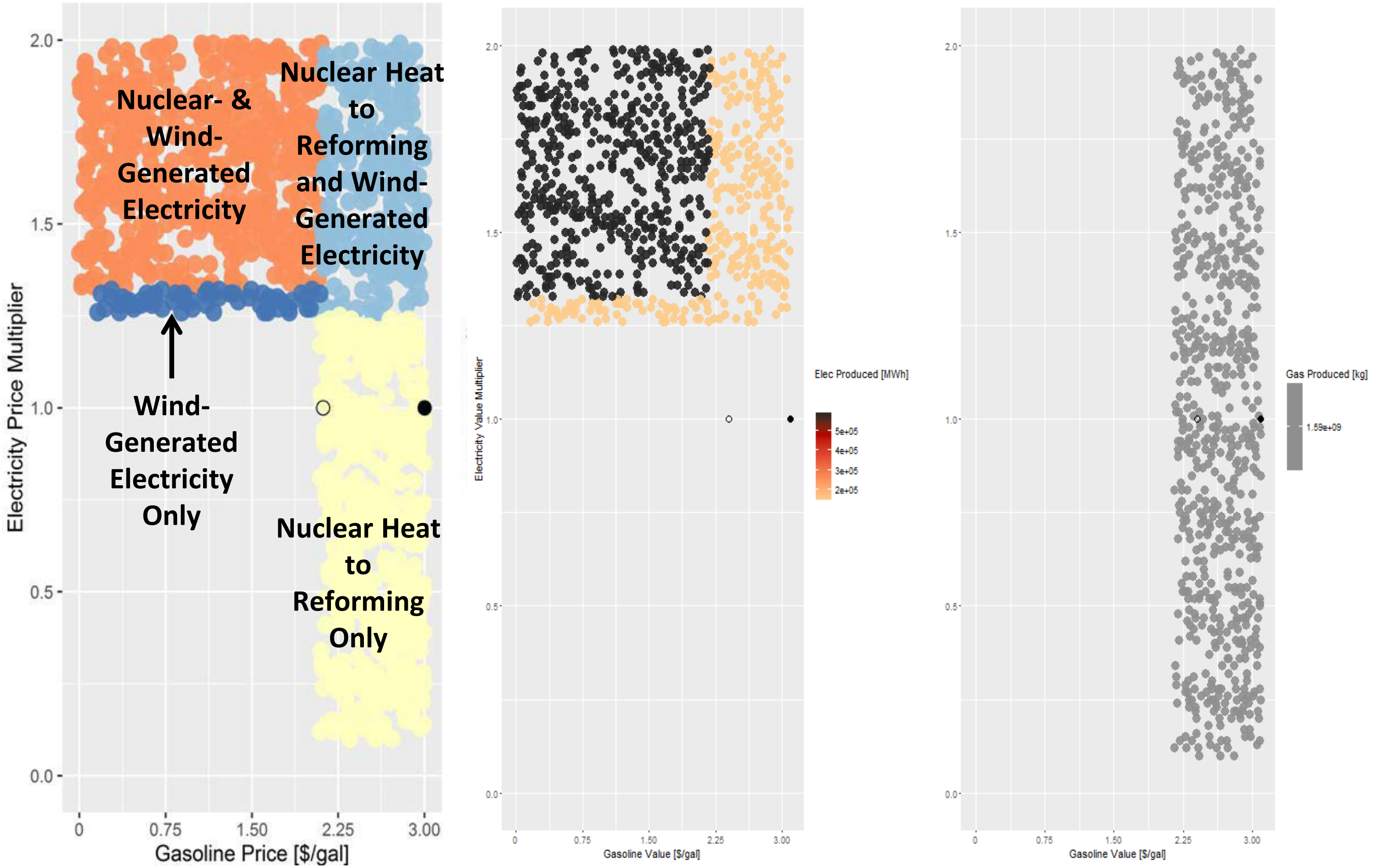
Under our analytical method and most of our assumptions, the primary driver for whether a subsystem is included in the optimal configuration is whether it would be profitable independently

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



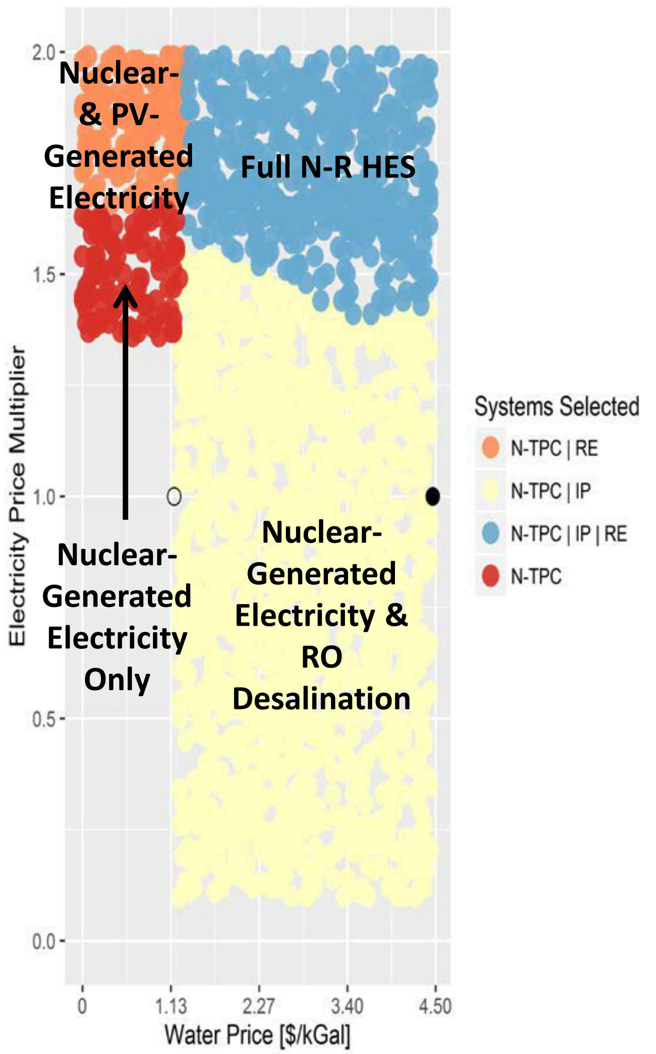
N-TPC: Nuclear reactor and thermal
N-IP: Nuclear reactor and industrial process
RE: Renewable electricity generation

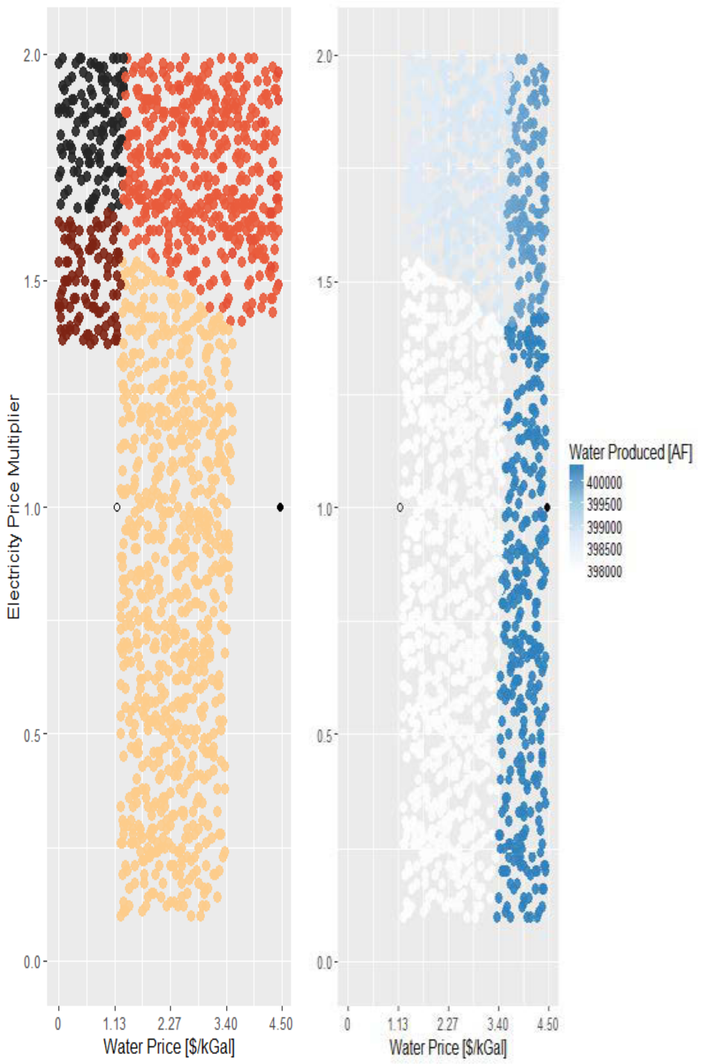
Conclusion #2:
Industrial processes usually maximize profitability by operating the maximum number of hours possible in a year

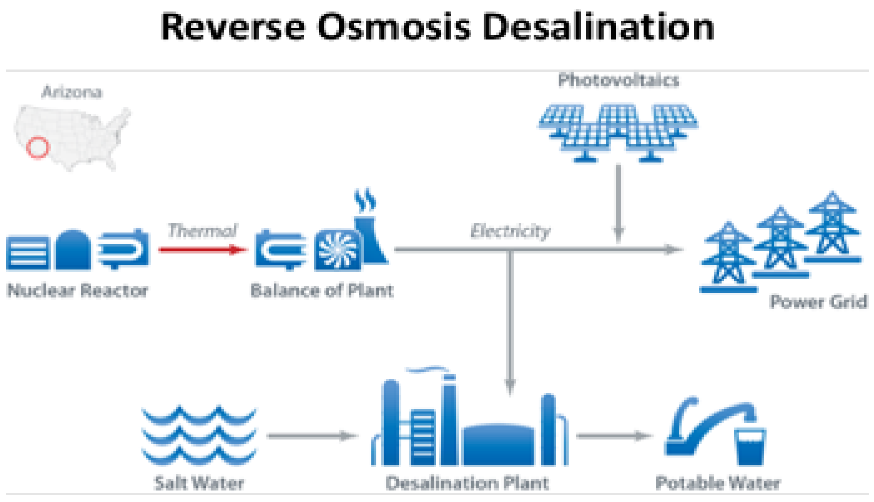
In other words:
Our electricity price assumptions are insufficiently volatile for arbitrage (even with high renewables & capacity payments)

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





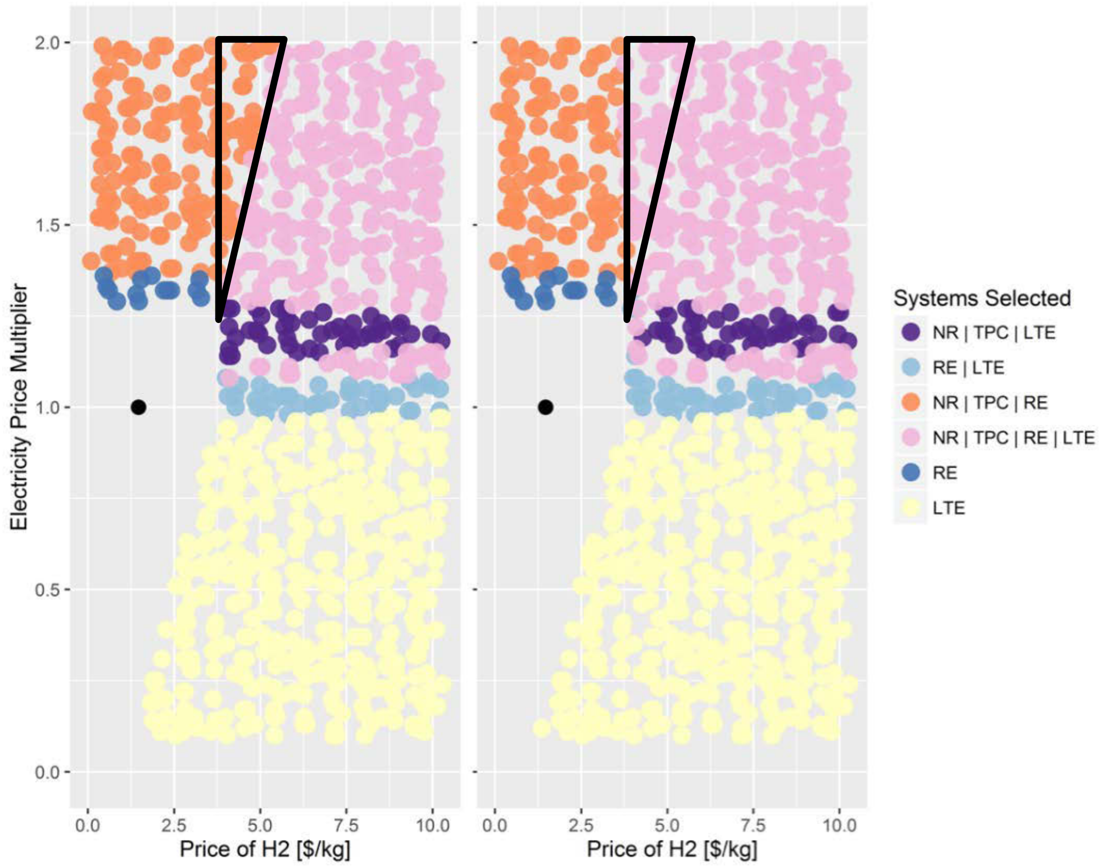


Exception to #2:
Systems with lower hourly income required from the industrial process may optimally reduce the industrial product to receive a capacity payment (white & lighter blue regions in water production graph)

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

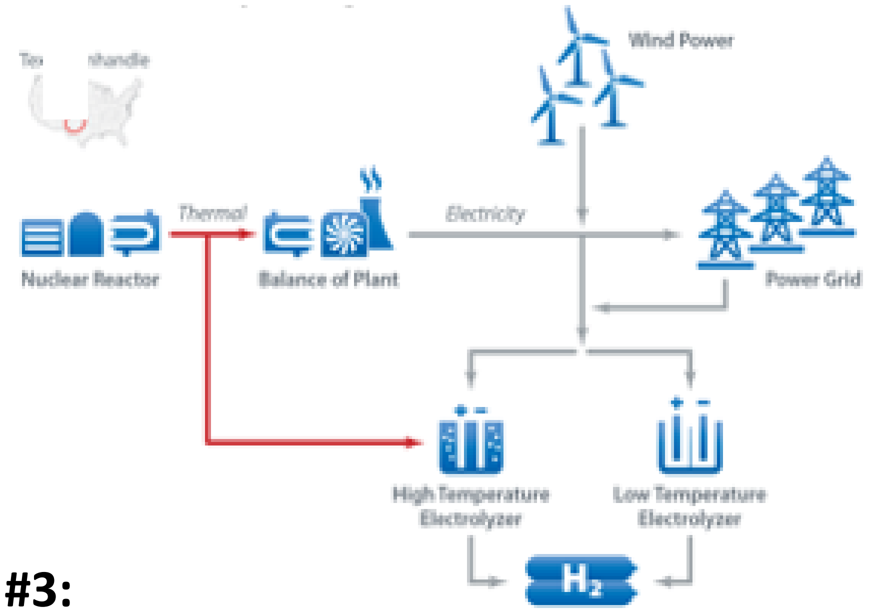
Flexibility Benefits N-R HESs with Lower Capital Cost Industrial Processes

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)

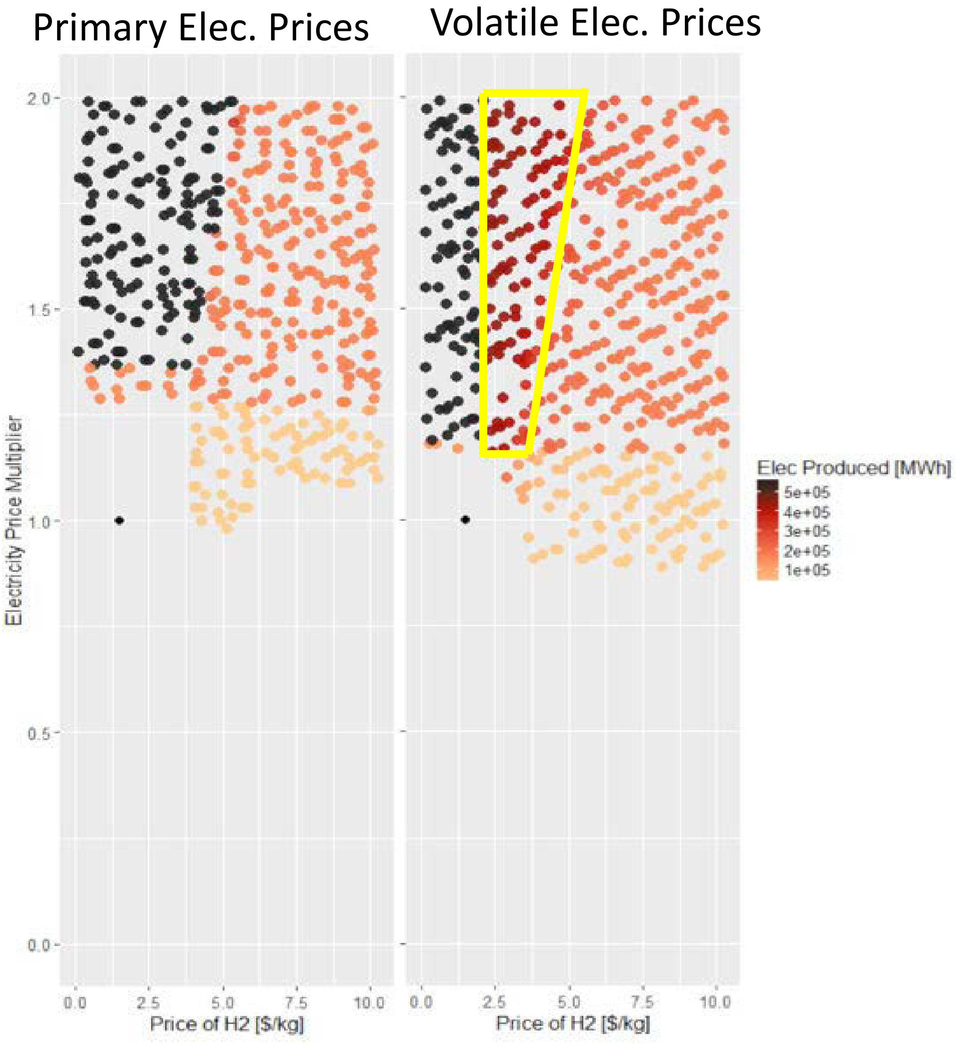


Conclusion #3:

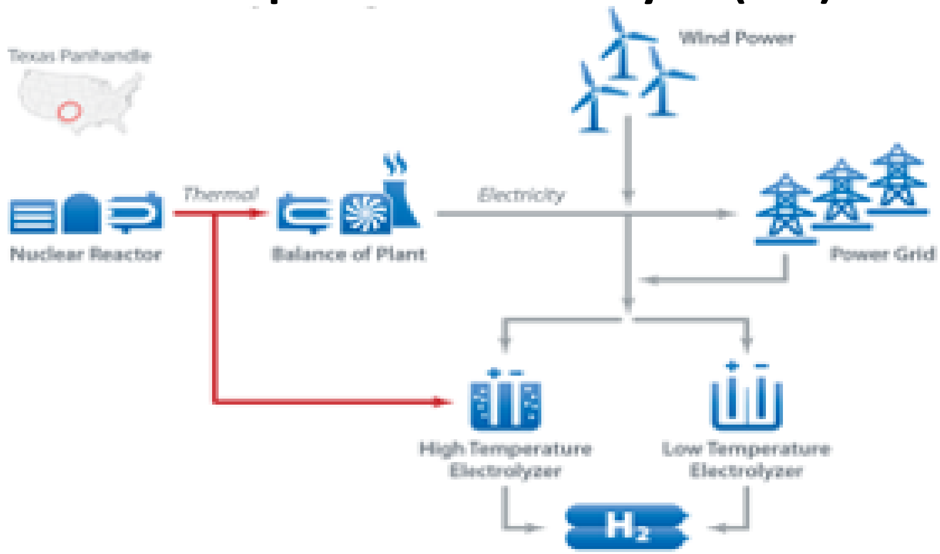
- Lower capital cost industrial processes are more likely to utilize their flexibility to switch between electricity and the industrial product more often than their higher capital cost configurations
- This flexibility increases the number of profitable situations

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



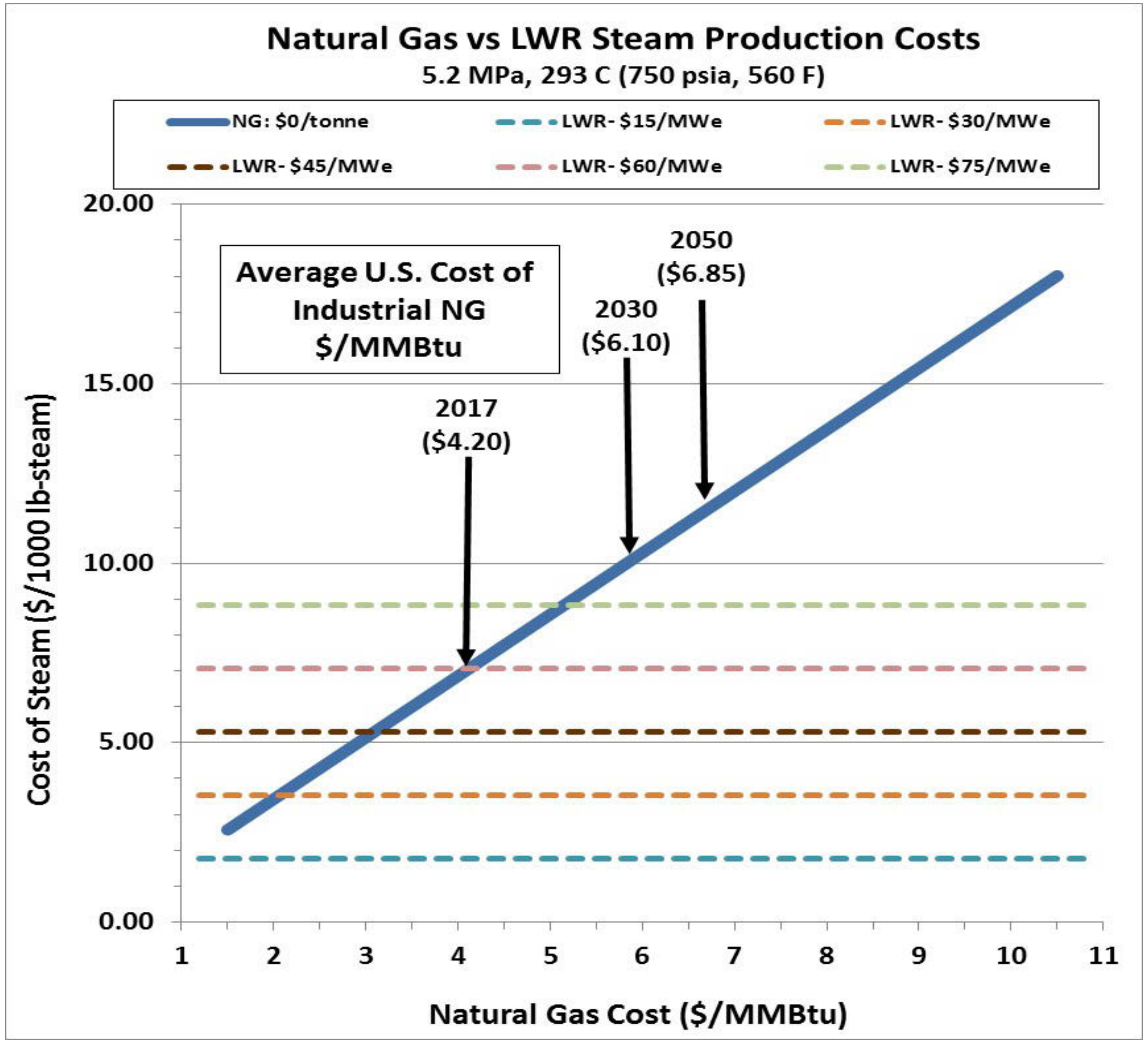
Low Temperature Electrolysis (LTE)



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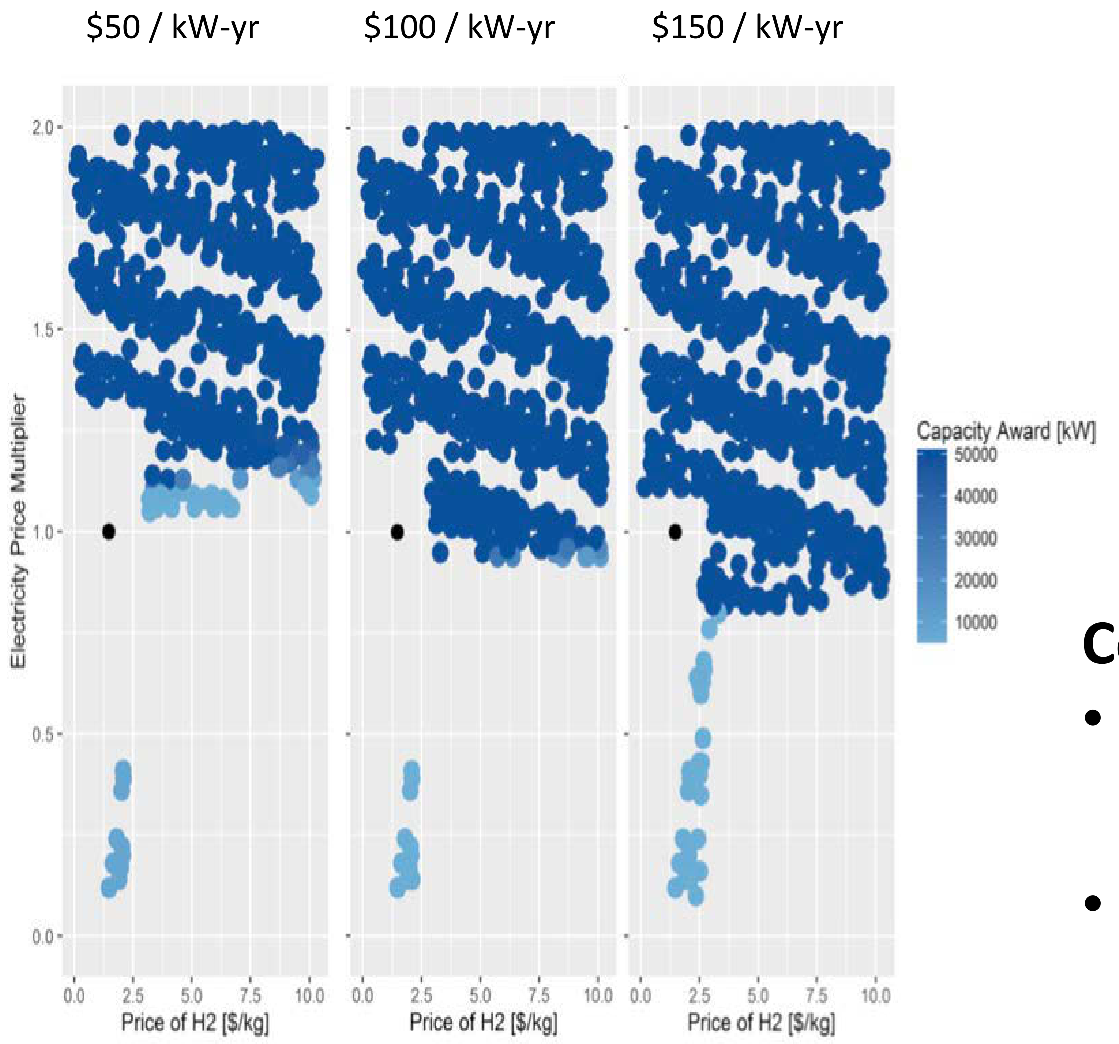
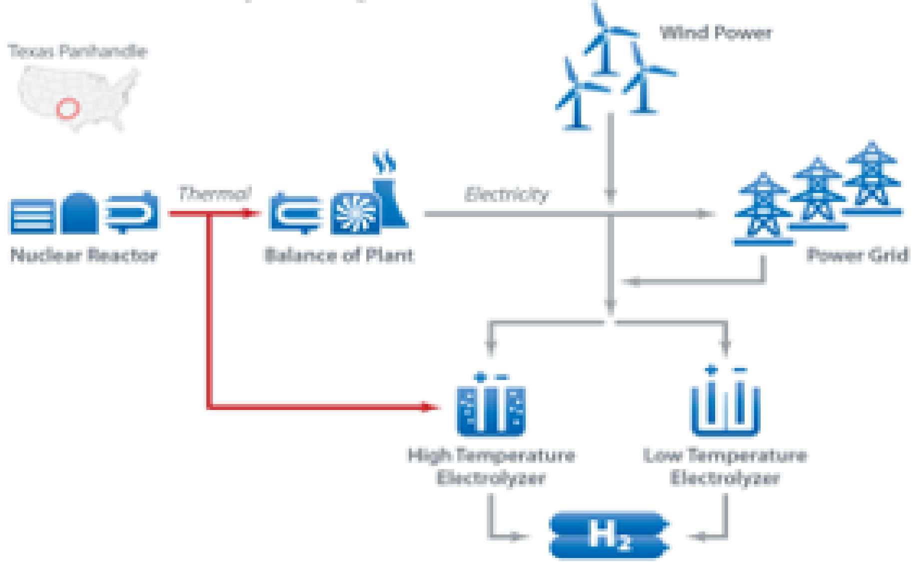
High Temperature Electrolysis N-R HES: Impact of Capacity Payments



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

Conclusions - 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

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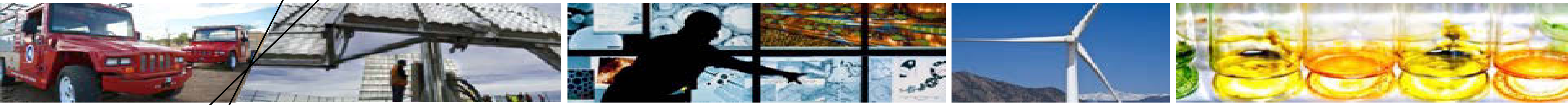

Thank you!

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