Joint Institute for Strategic Energy Analysis

The Potential for Nuclear in a Renewable Energy World

Mark F. Ruth

June 20, 2019

Colorado Renewable Energy Society Meeting

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:

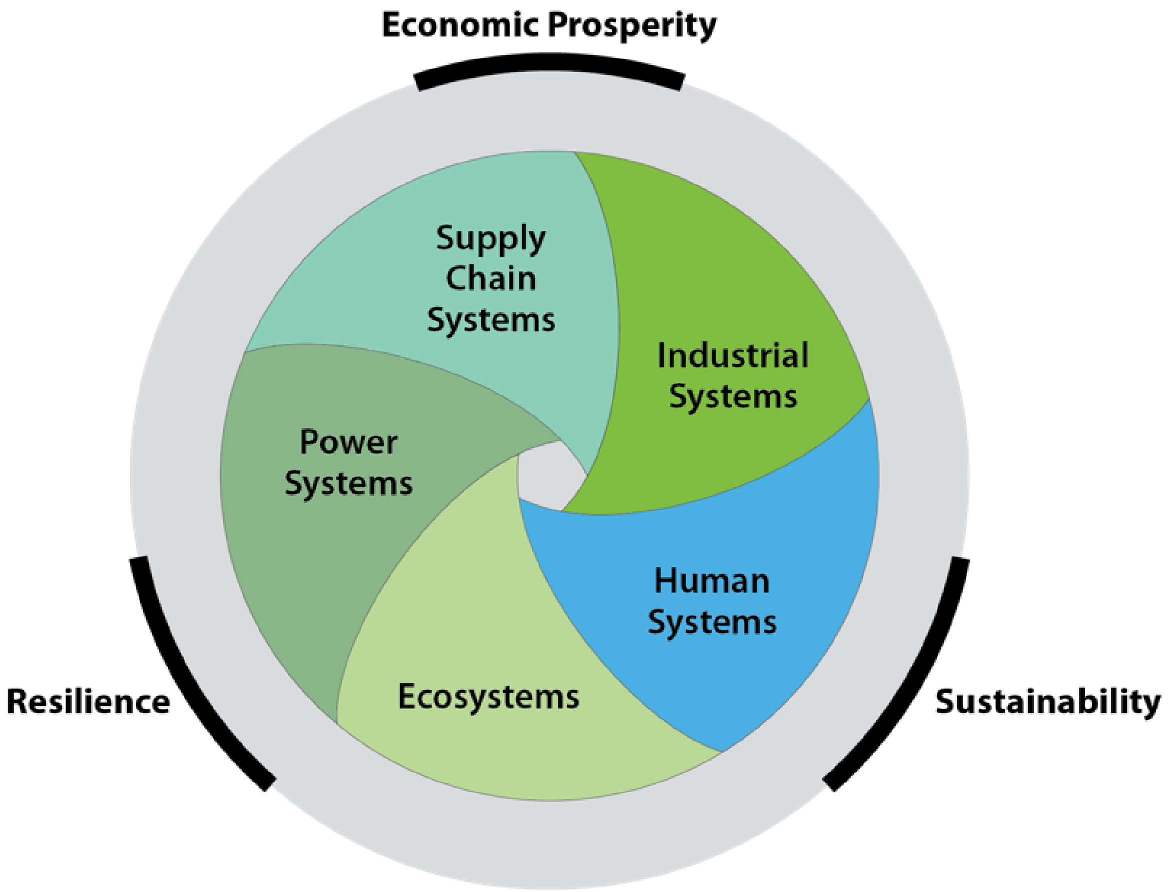
- 1800 employees, plus 400 postdoctoral researchers, interns, visiting professionals, and subcontractors
- 327-acre campus in Golden & 305-acre National Wind Technology Center 13 miles north
- 61 R&D 100 awards. More than 1000 scientific and technical materials published annually

www.nrel.gov/about

JISEA

Joint Institute for Strategic Energy Analysis

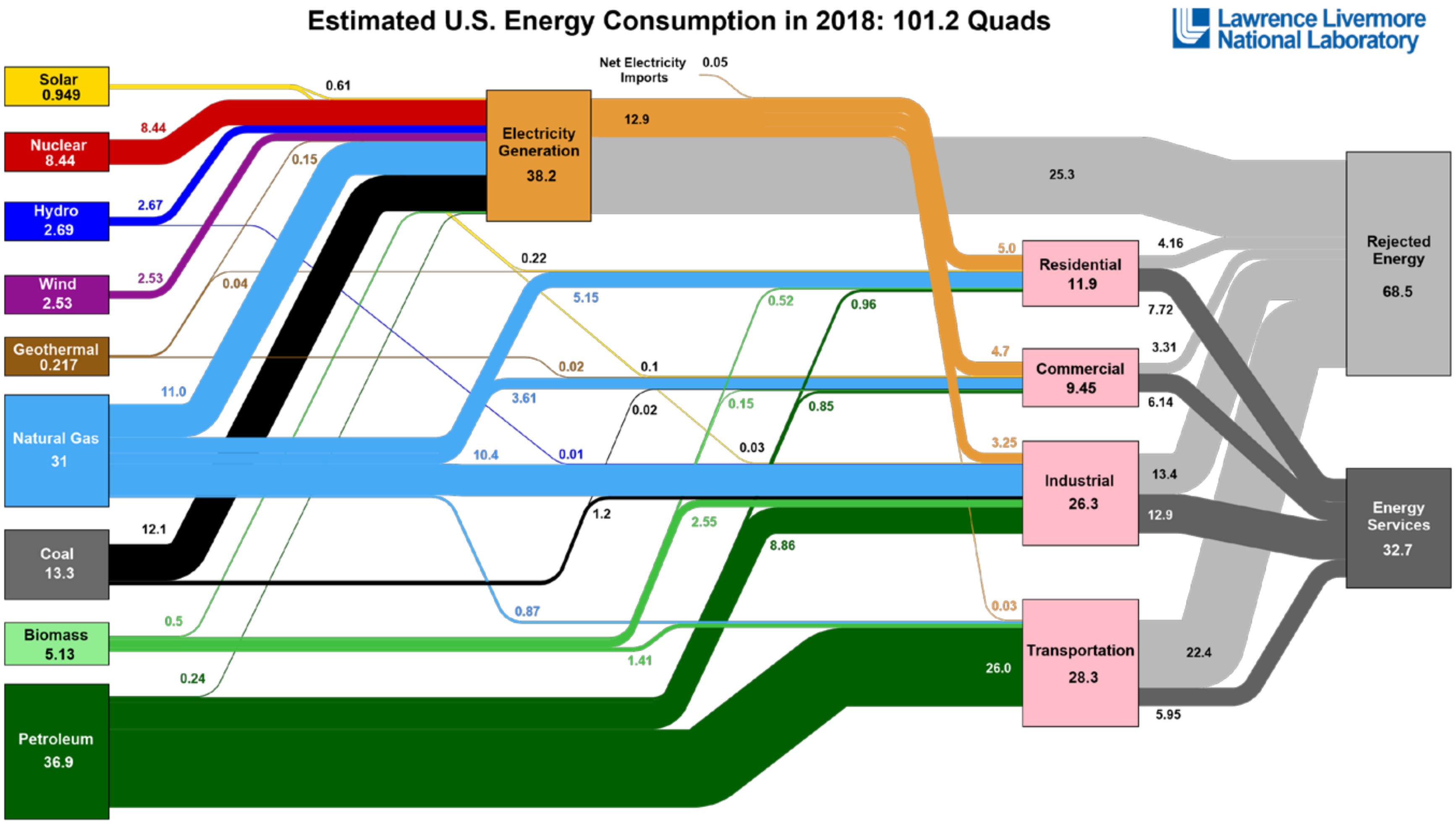
Connecting technologies, economic sectors, and continents to catalyze the transition to the 21st century energy economy.



Founding Members

NREL National Renewable Energy Laboratory · Colorado School of Mines · Colorado State University · Massachusetts Institute of Technology · Stanford University · University of Colorado Boulder

Nuclear’s Role in Today’s Energy System



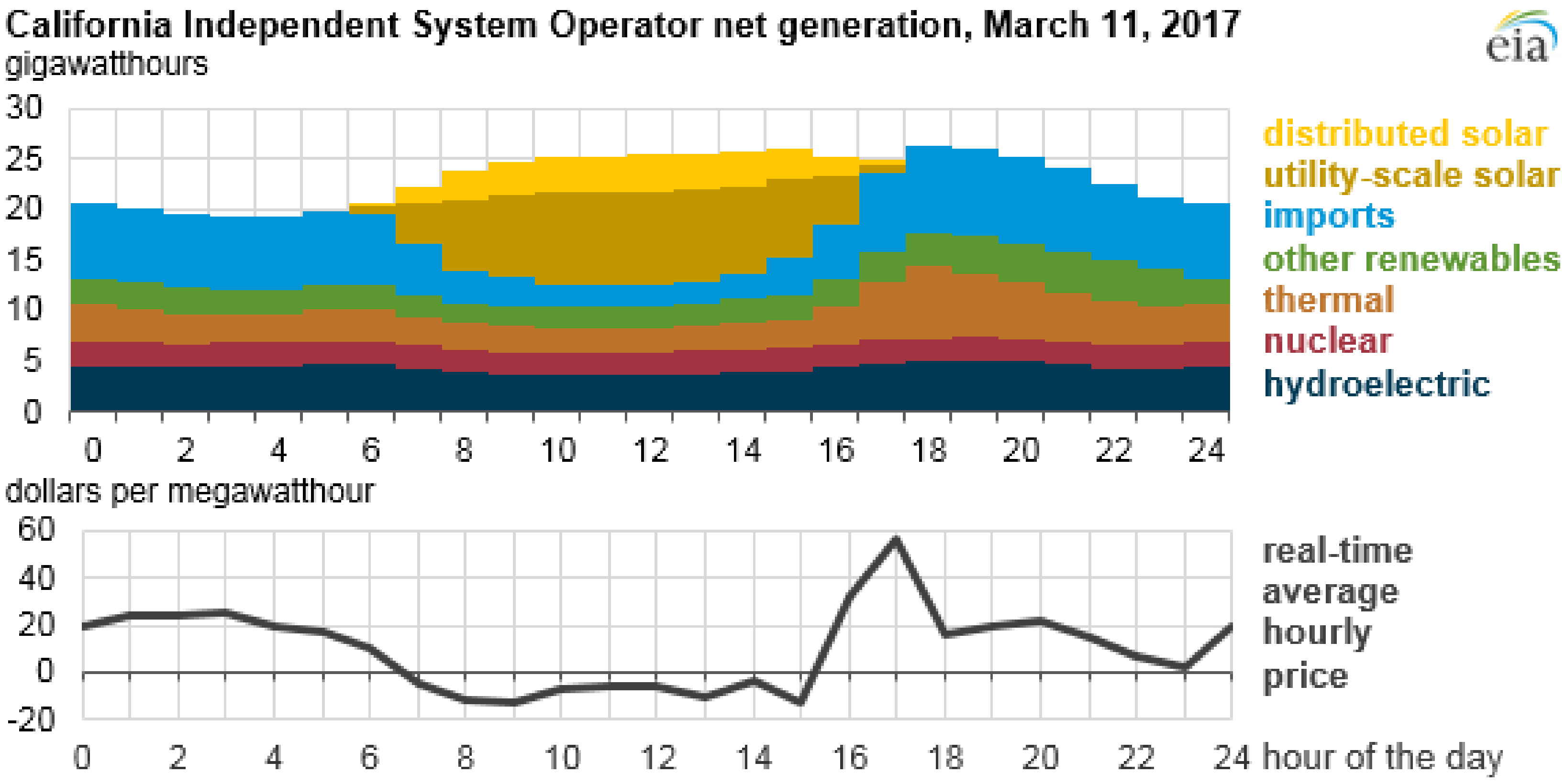
Source: LLNL March, 2019. Data is based on DOE/EIA MER (2018). If this information or a reproduction of it is used, credit must be given to the Lawrence Livermore National Laboratory and the Department of Energy, under whose auspices the work was performed. Distributed electricity represents only retail electricity sales and does not include self-generation. EIA reports consumption of renewable resources (i.e., hydro, wind, geothermal and solar) for electricity in BTU-equivalent values by assuming a typical fossil fuel plant heat rate. The efficiency of electricity production is calculated as the total retail electricity delivered divided by the primary energy input into electricity generation. End use efficiency is estimated as 65% for the residential sector, 65% for the commercial sector, 21% for the transportation sector and 49% for the industrial sector, which was updated in 2017 to reflect DOE's analysis of manufacturing. Totals may not equal sum of components due to independent rounding. LLNL-MI-410527

More electricity is generated from nuclear sources than all renewable sources combined.

All substantial nuclear energy use in the U.S. for electricity

The U.S. produces more nuclear energy than any other nation

Electricity Sector Evolution

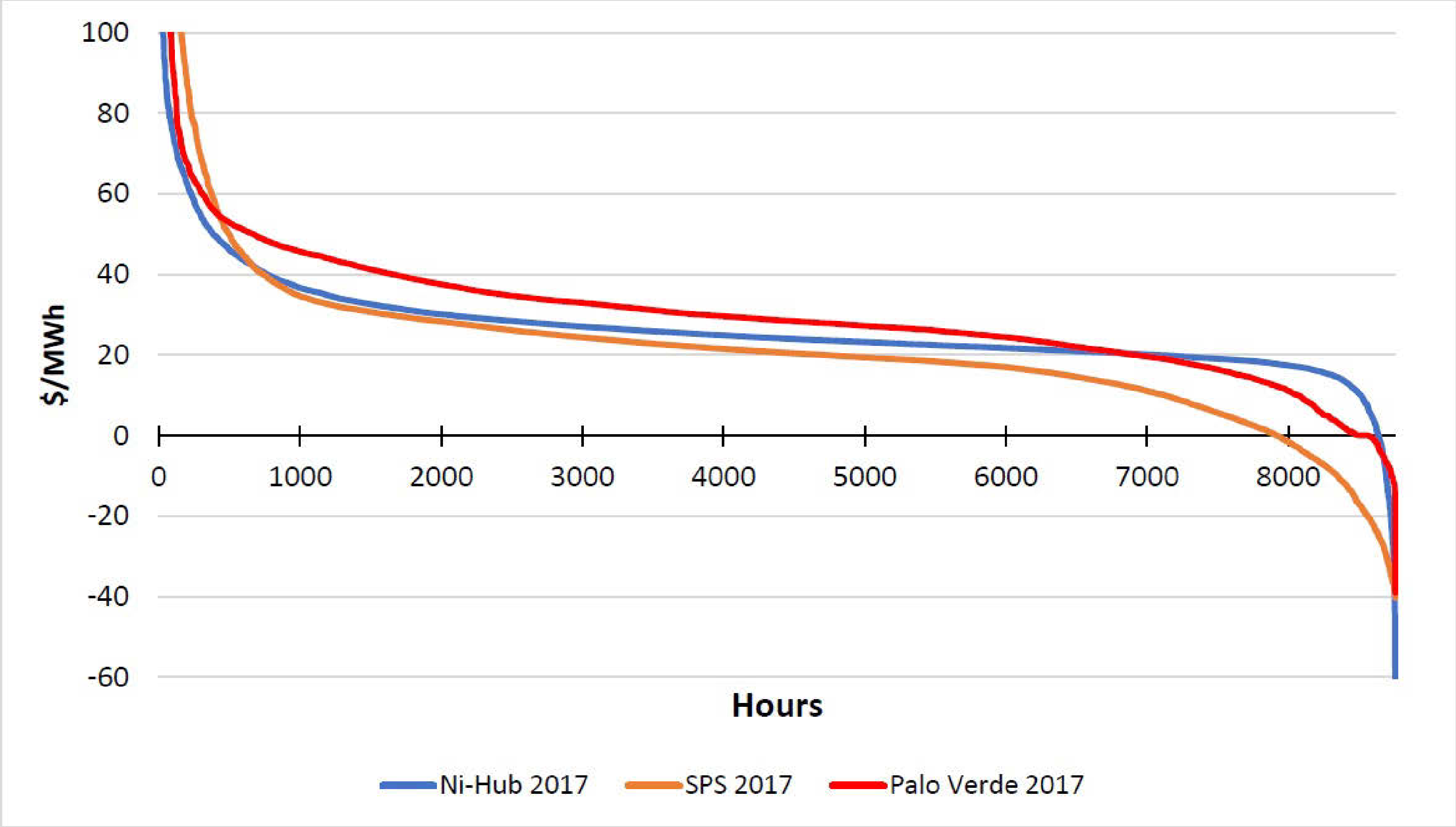


Source: **U.S. Energy Information Administration,** "Rising Solar Generation in California Coincides with Negative Wholesale Electricity Prices," EIA, Today in Energy, https://www.eia.gov/todayinenergy/detail.php?id=30692#tab4 (Apr. 7, 2017).

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.

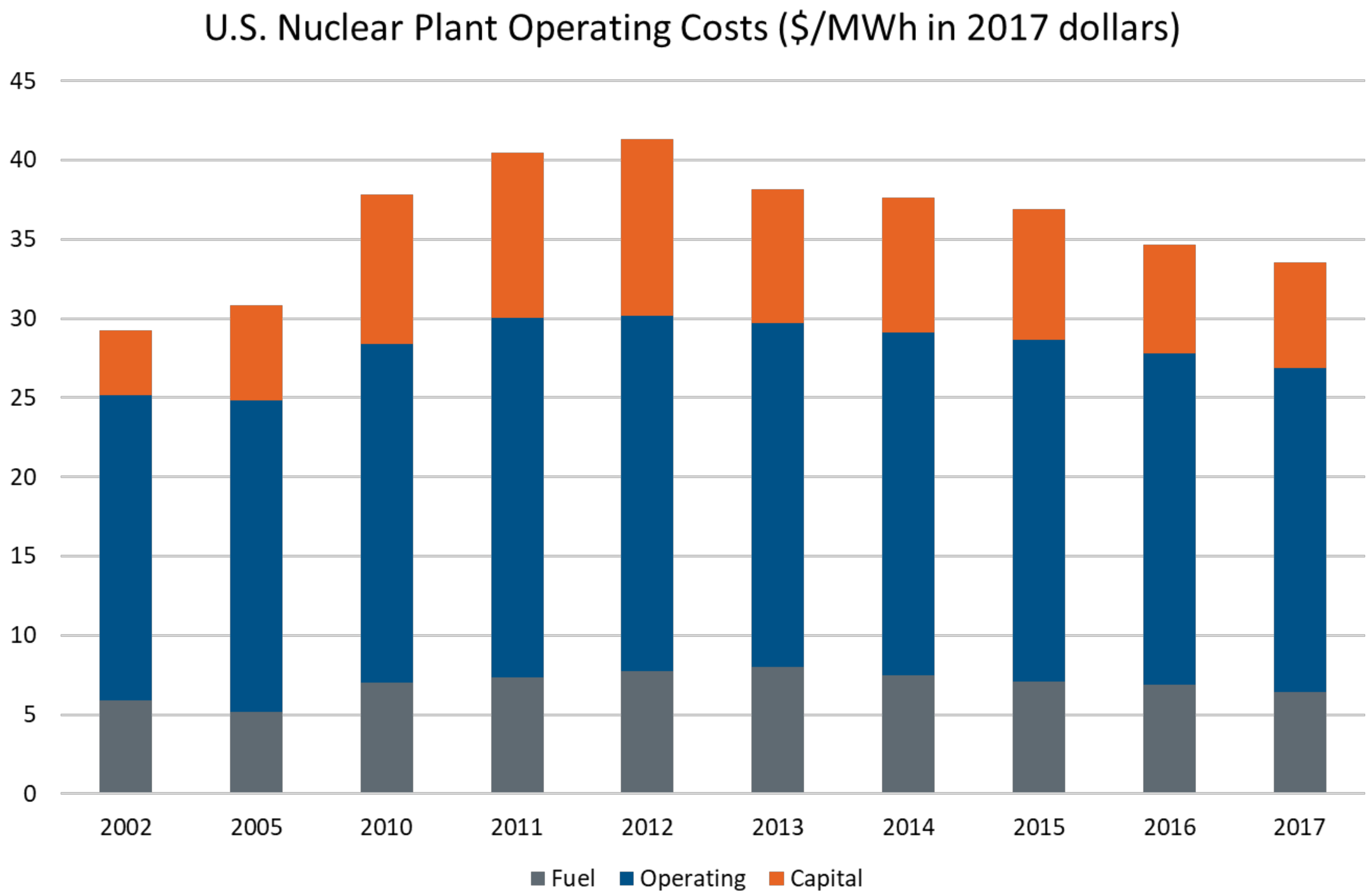
Reduced and Volatile Electricity Prices



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



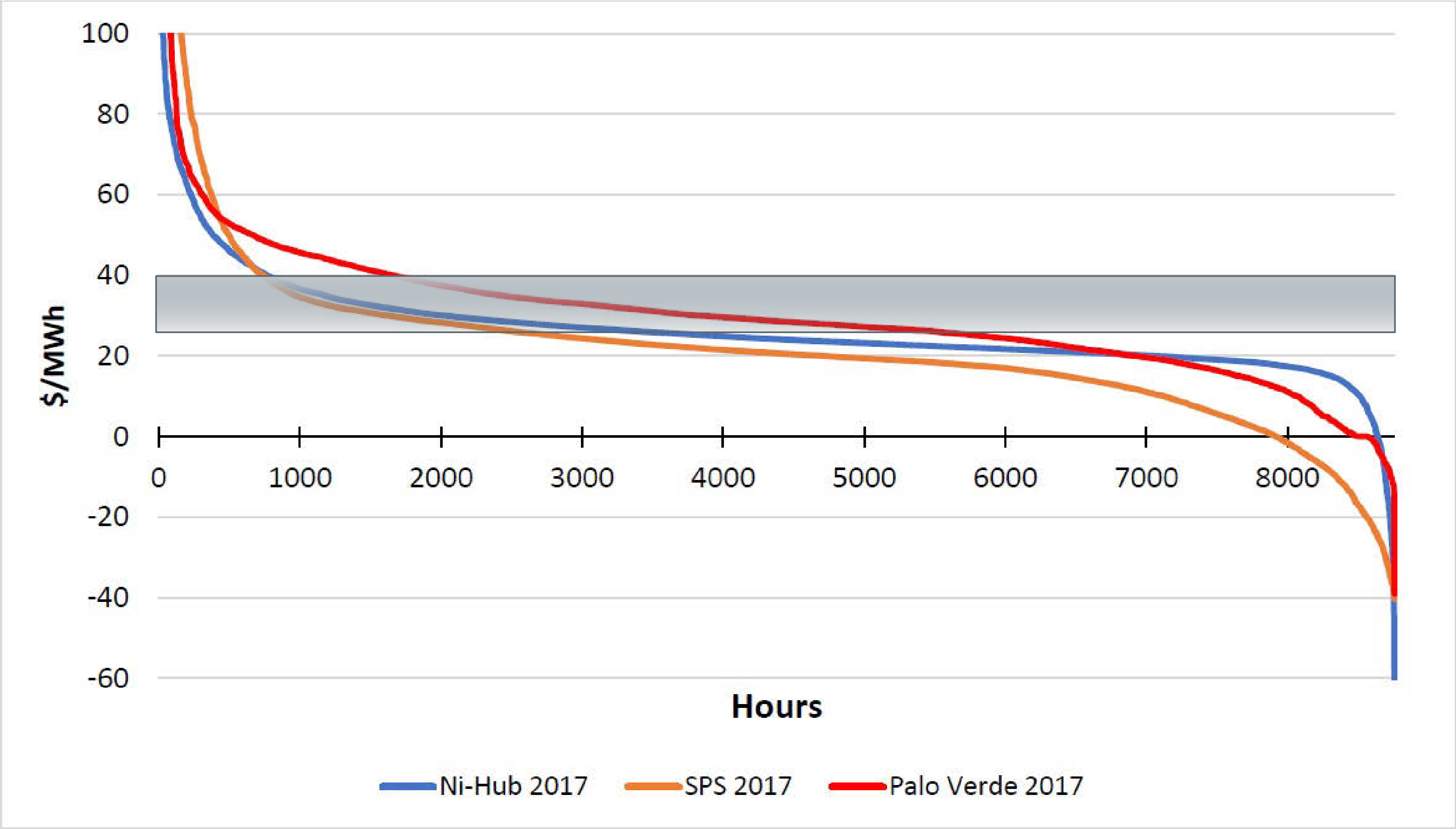
Operating costs of nuclear plants are not negligible.

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).

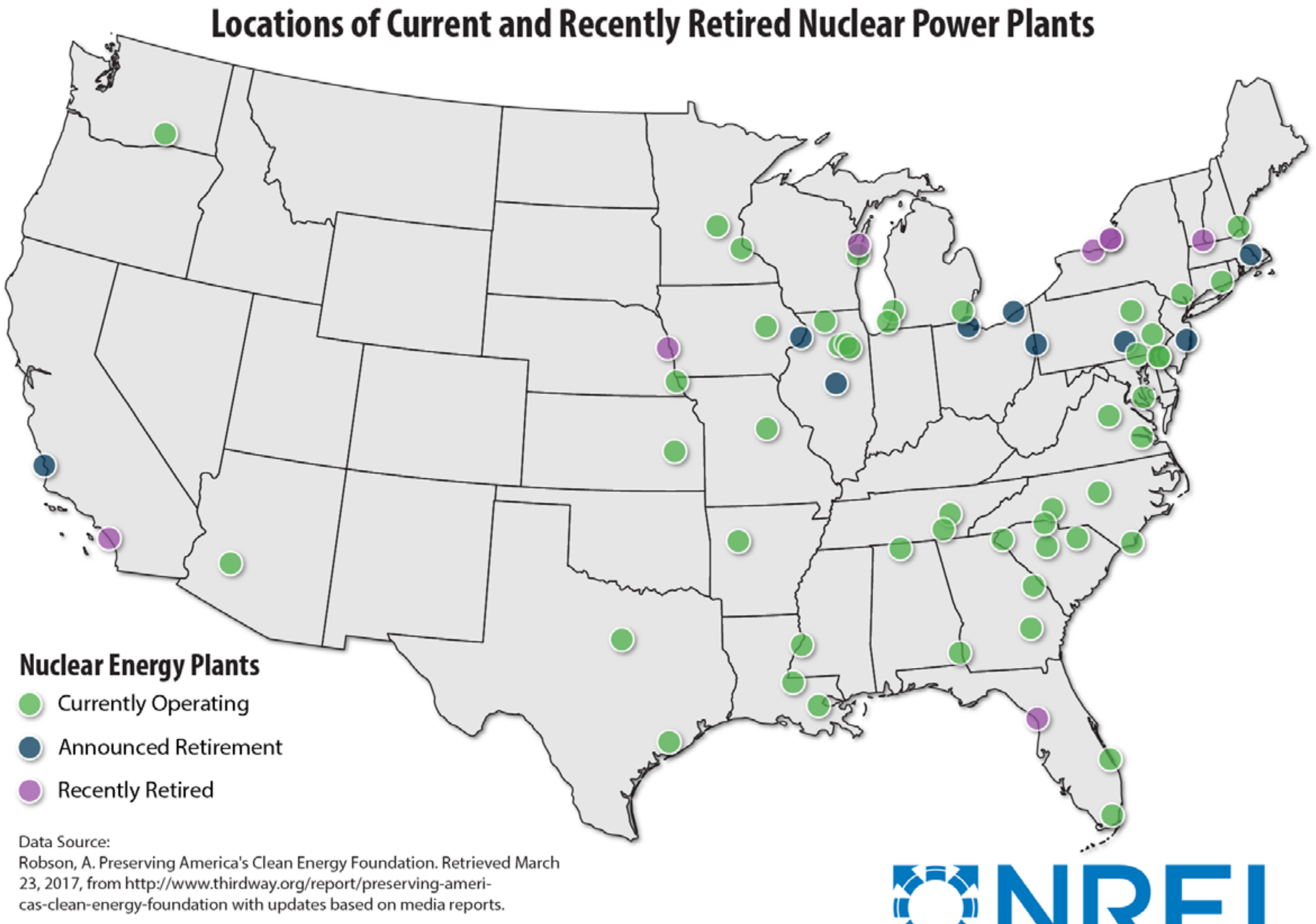
Reduced and Volatile Electricity Prices are a Challenge



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.

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

Electricity Price Impacts on Nuclear Power Plants



Thus, many have minimal profit margins and others are shutting down. New nuclear power plants are unlikely to be built.

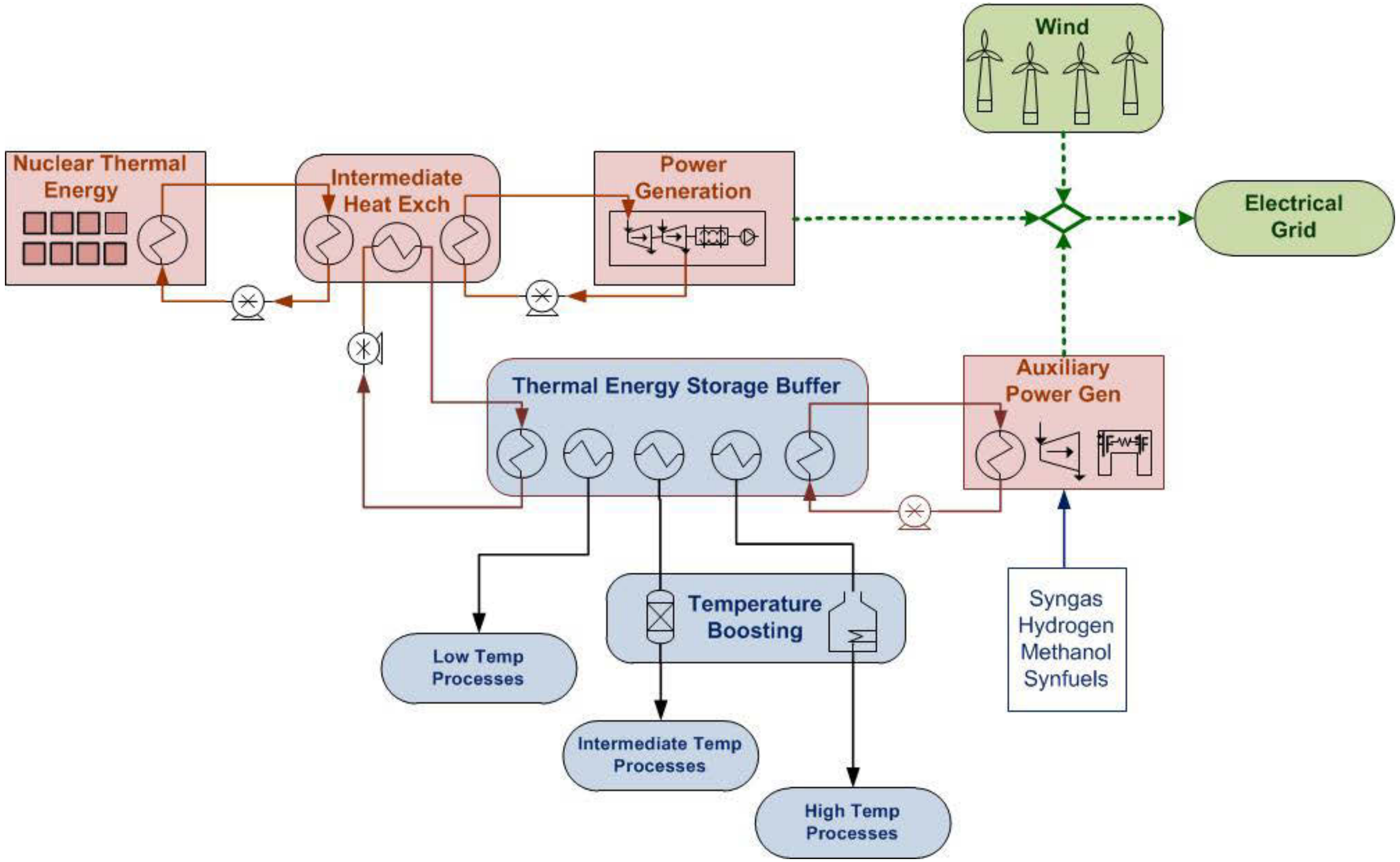
What is a possible solution?

Flexible Generation

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)

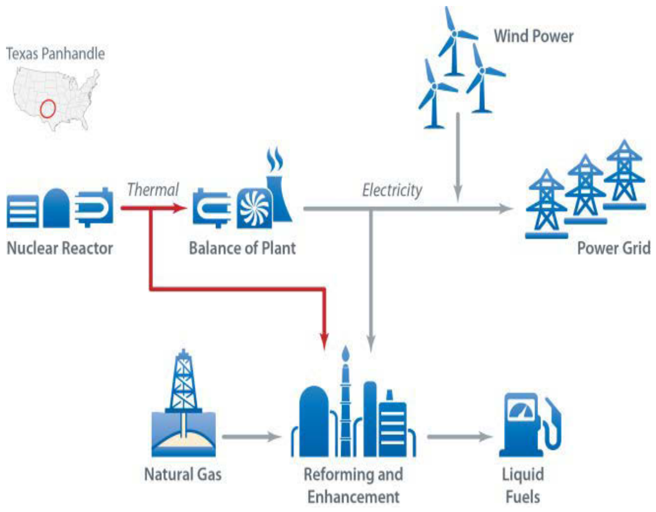
JISEA's Analysis

- 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

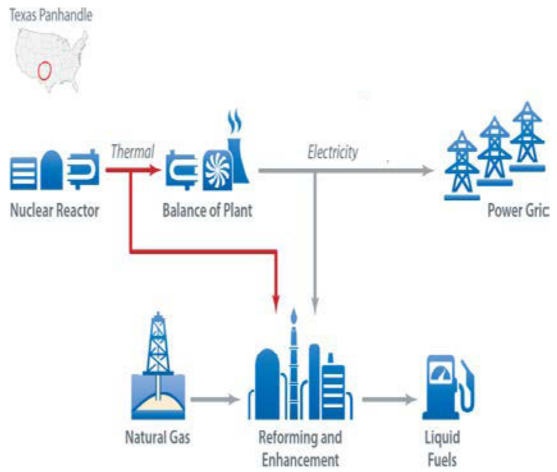
Analysis Methodology

Identify optimal configurations and internal dispatch under various product prices

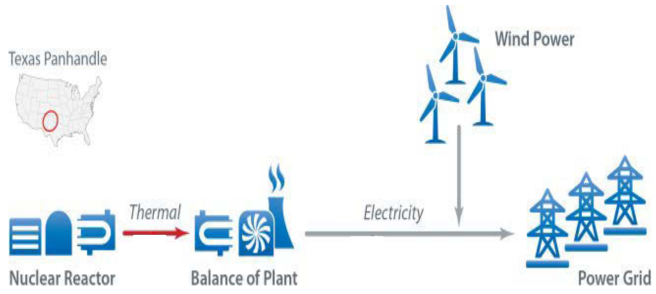
Full Configuration



Partial Configuration



Another Partial Configuration



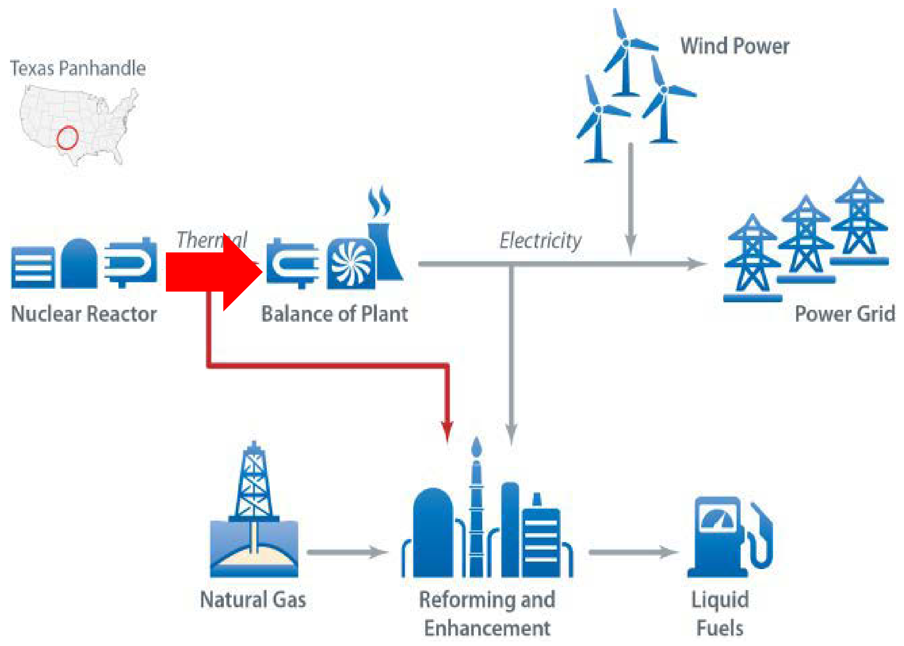
Other configurations: (1) nuclear-generated electricity only and (2) wind only

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

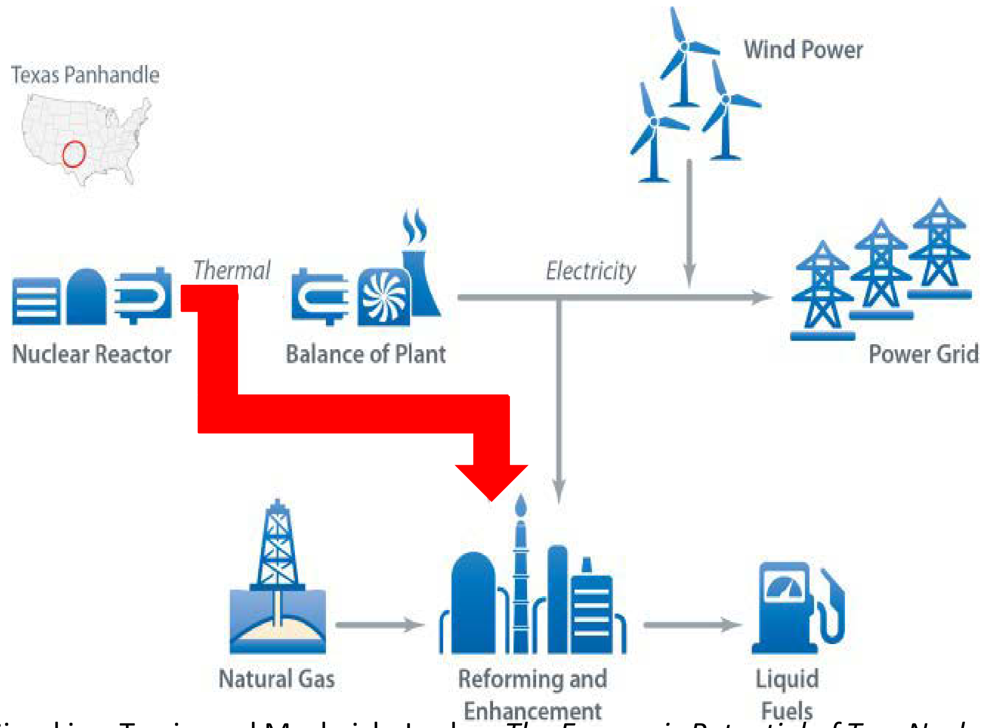
Analysis Methodology

Identify optimal configurations and
internal dispatch under various product prices

One Dispatch Option

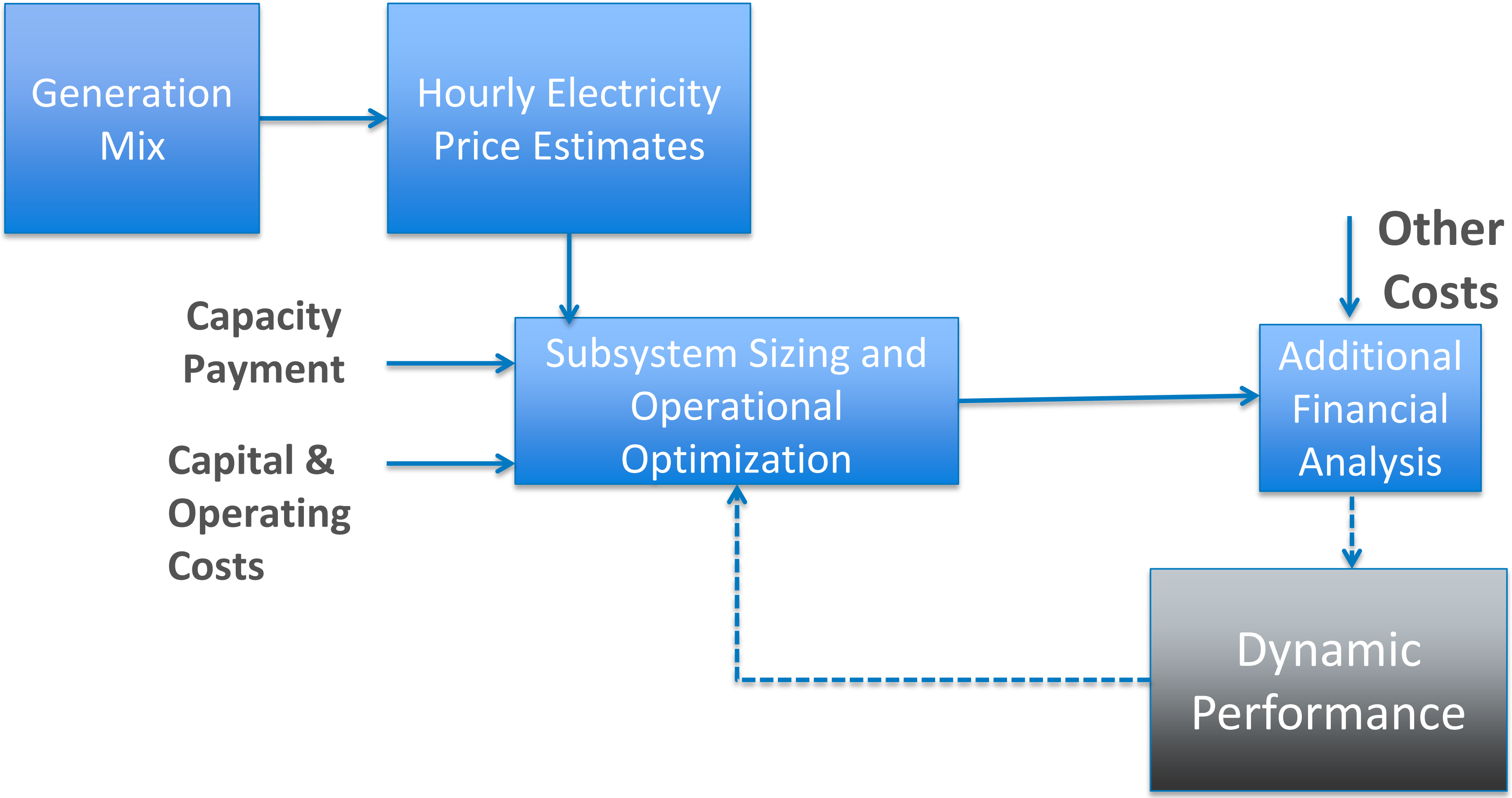


Second Dispatch Option



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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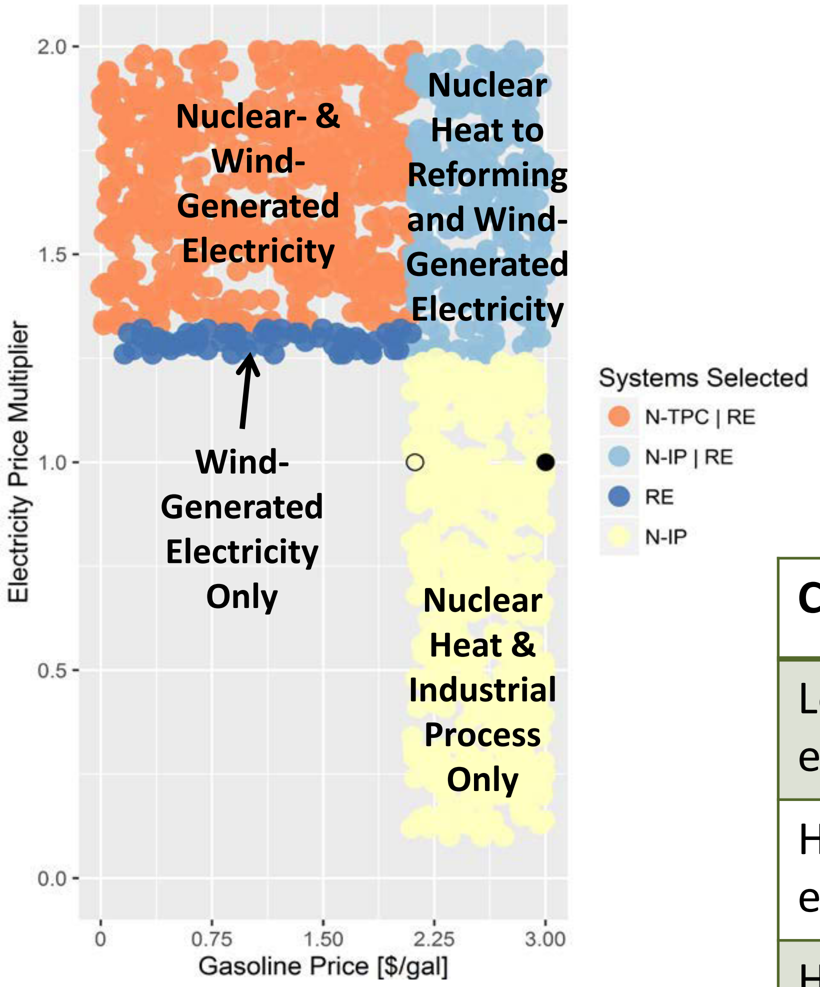
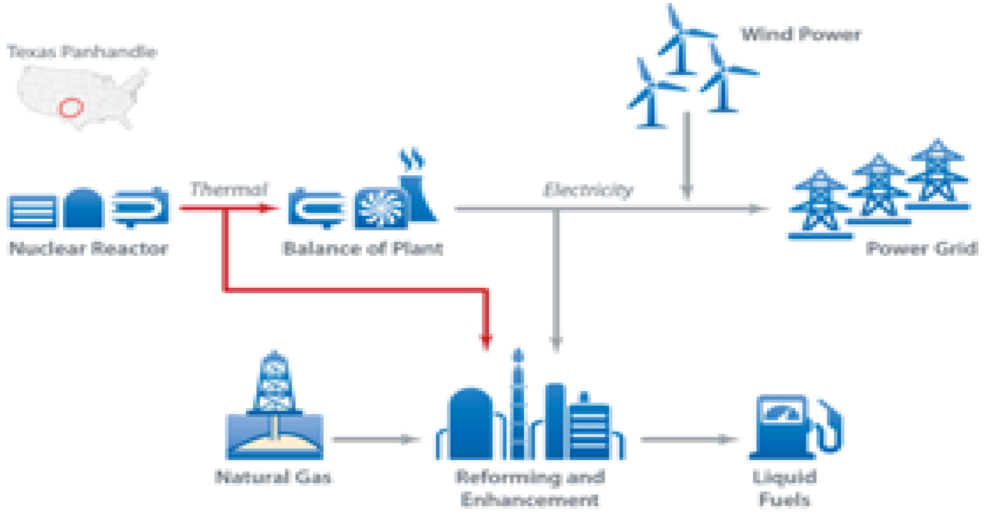
Optimal Configurations Liquid Fuels Use Case



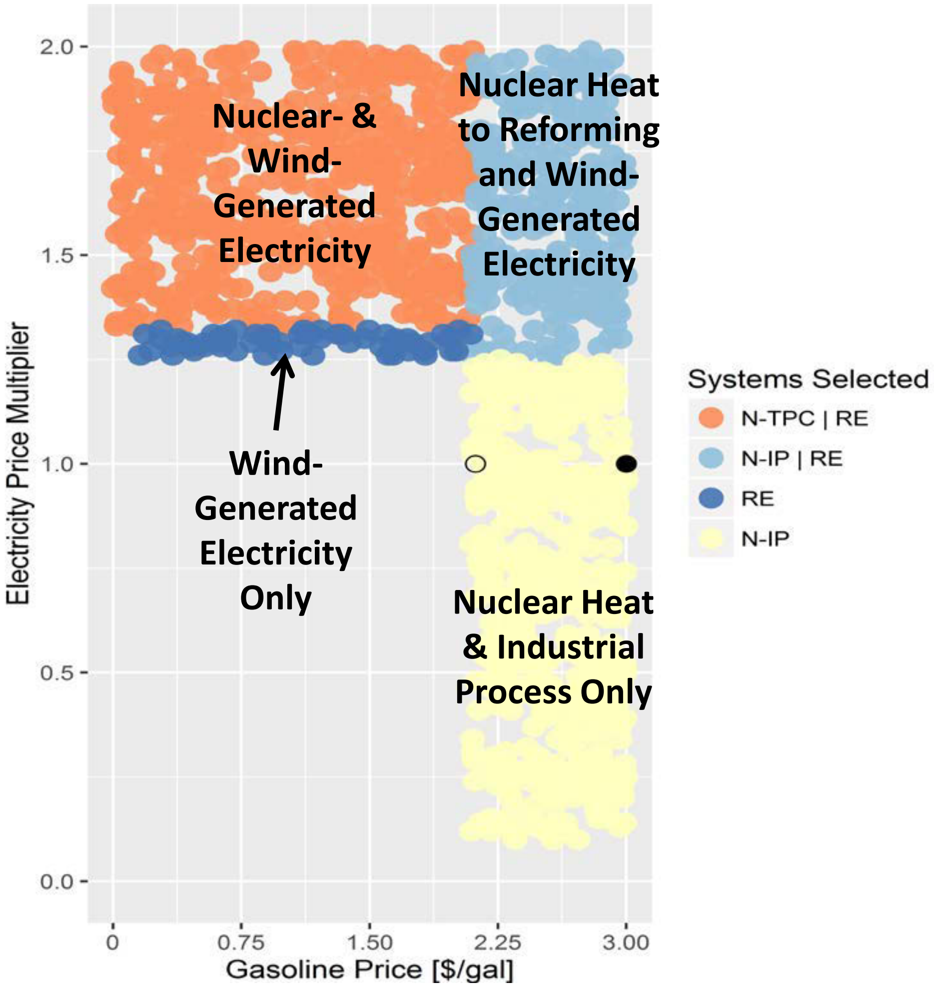
N-TPC: Nuclear reactor and thermal
N-IP: Nuclear reactor and industrial process
RE: Renewable electricity generation



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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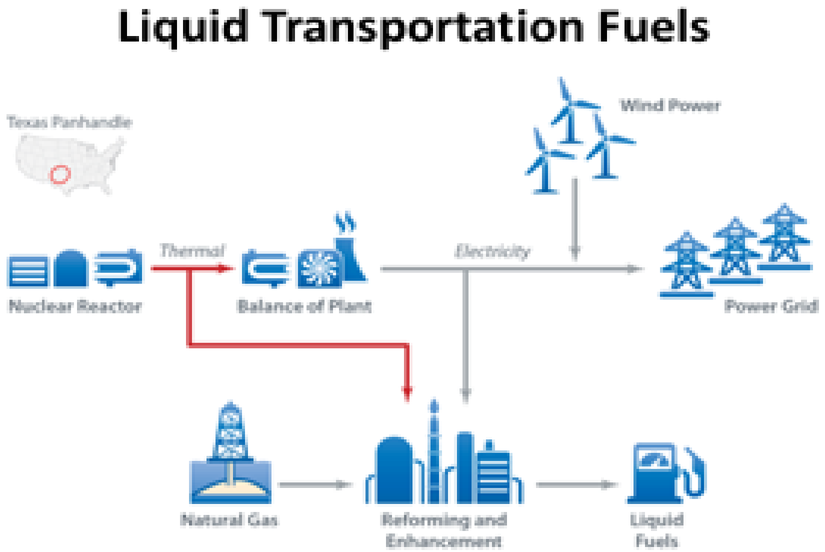


Conclusion #1:

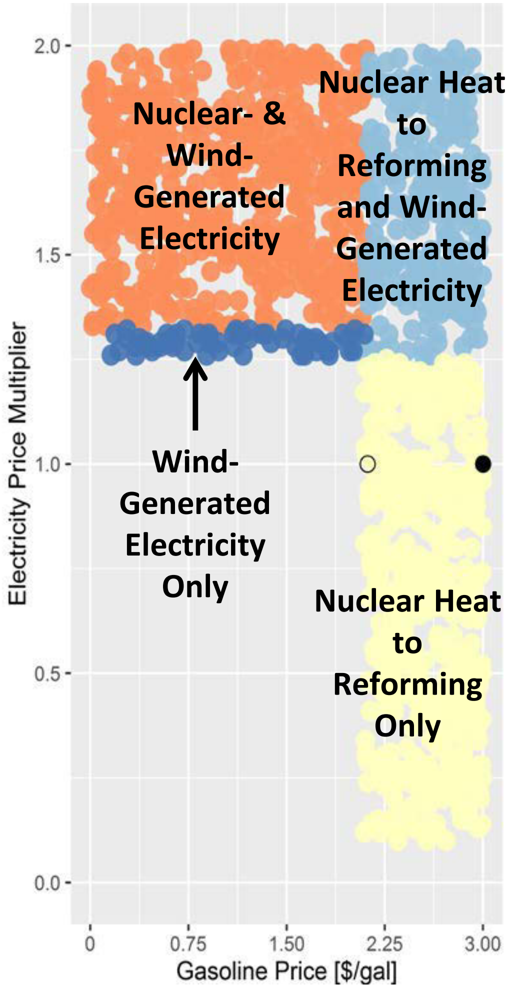
Under our analytical method and most of our assumptions, the primary driver for whether a subsystem is included in the optimal configuration is whether it would be profitable independently

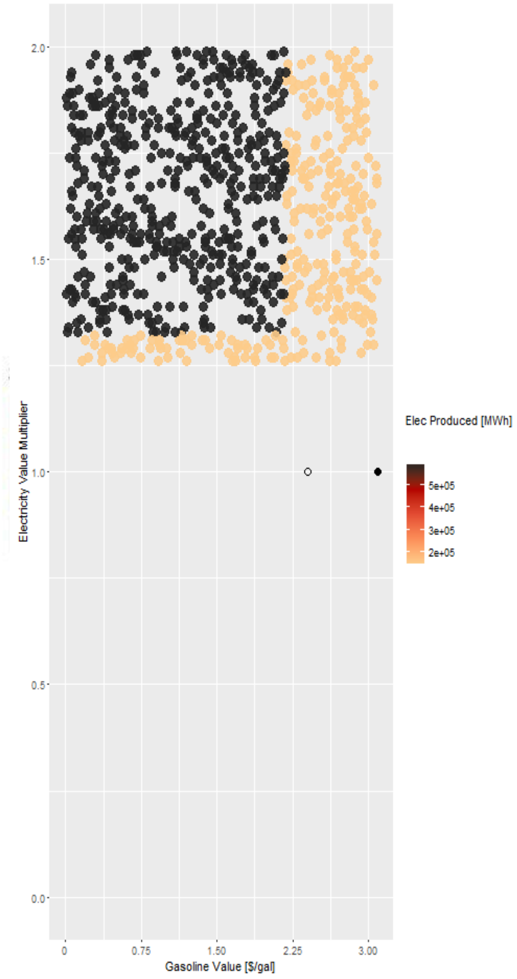
Major Caveats:

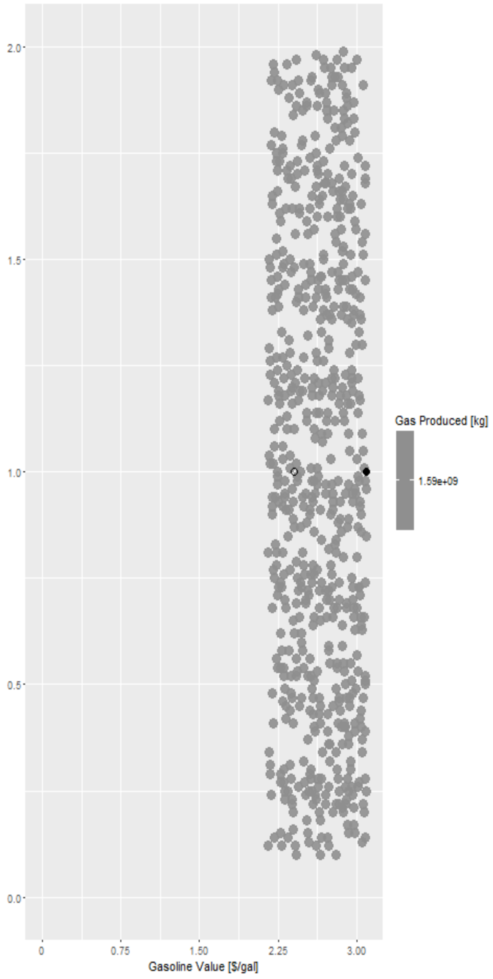
- Negligible grid connection costs
- No value for inertia or resilience

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

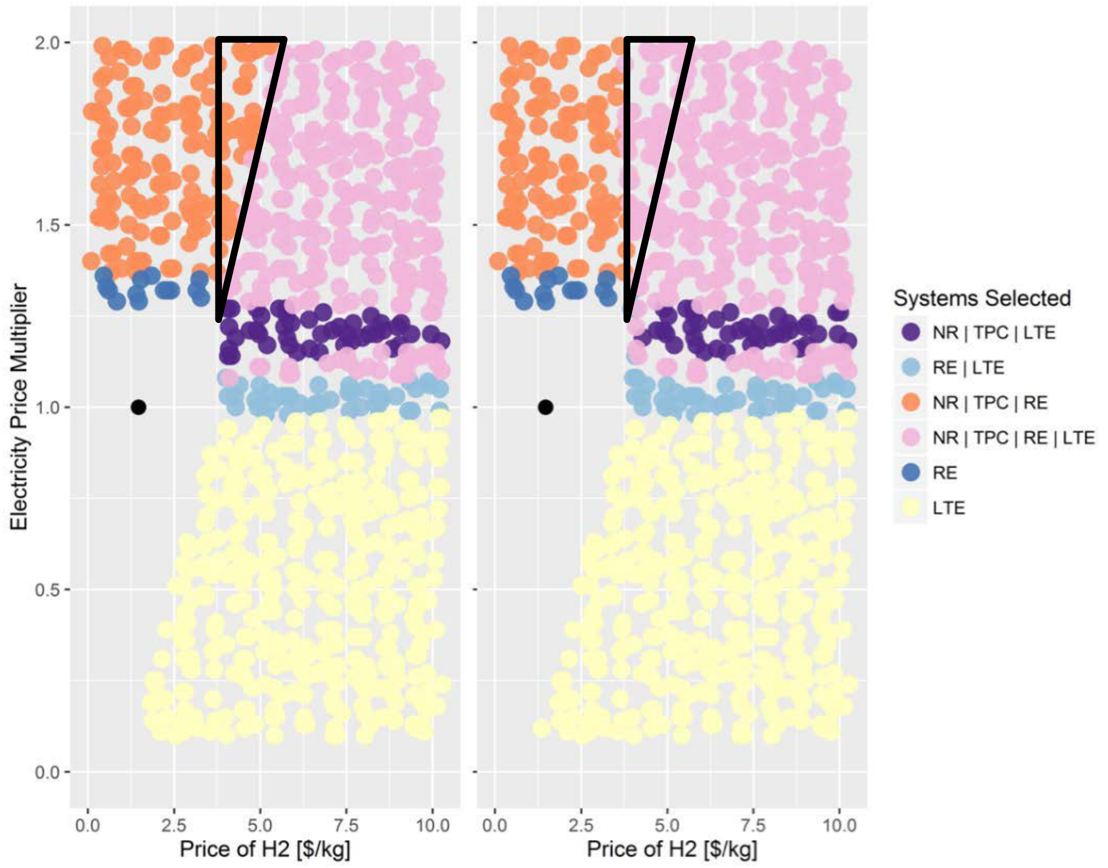
Conclusion #2:
Industrial processes usually maximize profitability by operating the maximum number of hours possible in a year

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

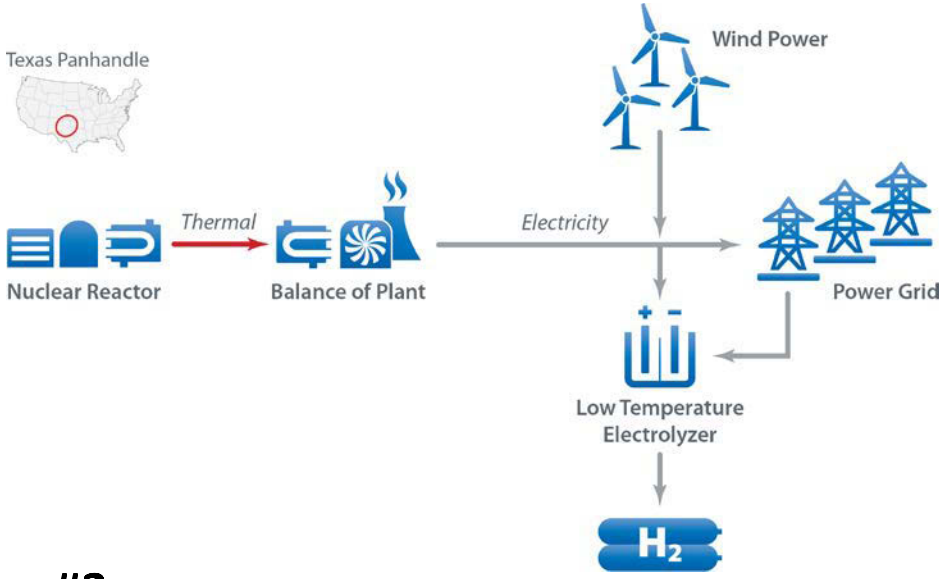
Flexibility Benefits N-R HESs with Lower Capital Cost Industrial Processes

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:

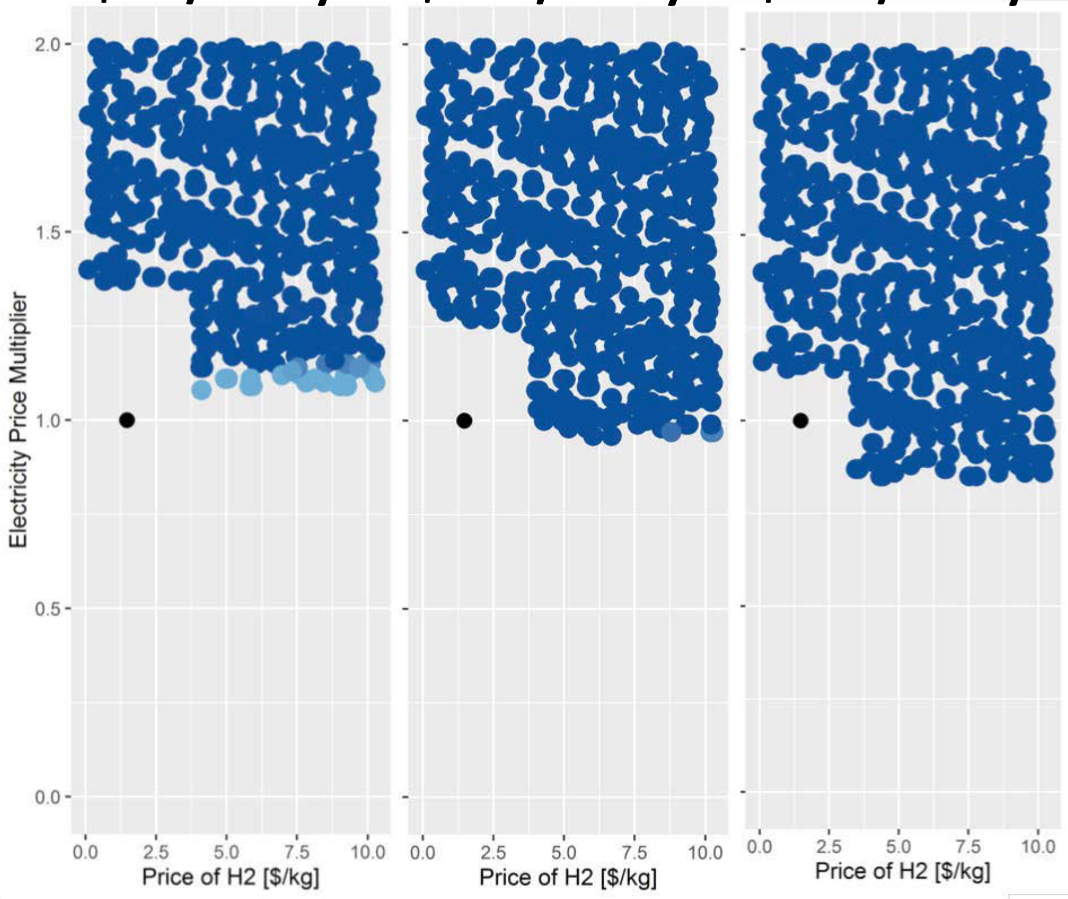
- Lower capital cost industrial processes are more likely to utilize their flexibility to switch between electricity and the industrial product more often than their higher capital cost configurations
- This flexibility increases the number of profitable situations

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

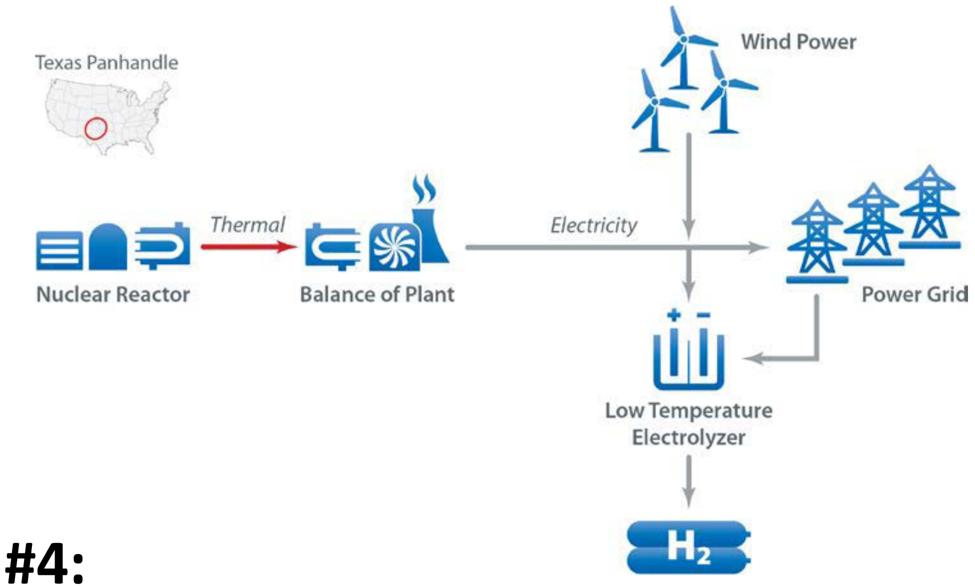
N-R HESs are More Competitive in Grids that Require Capacity

Capacity Payment

$50 / kW-yr $100 / kW-yr $150 / kW-yr



Low Temperature Electrolysis (LTE)

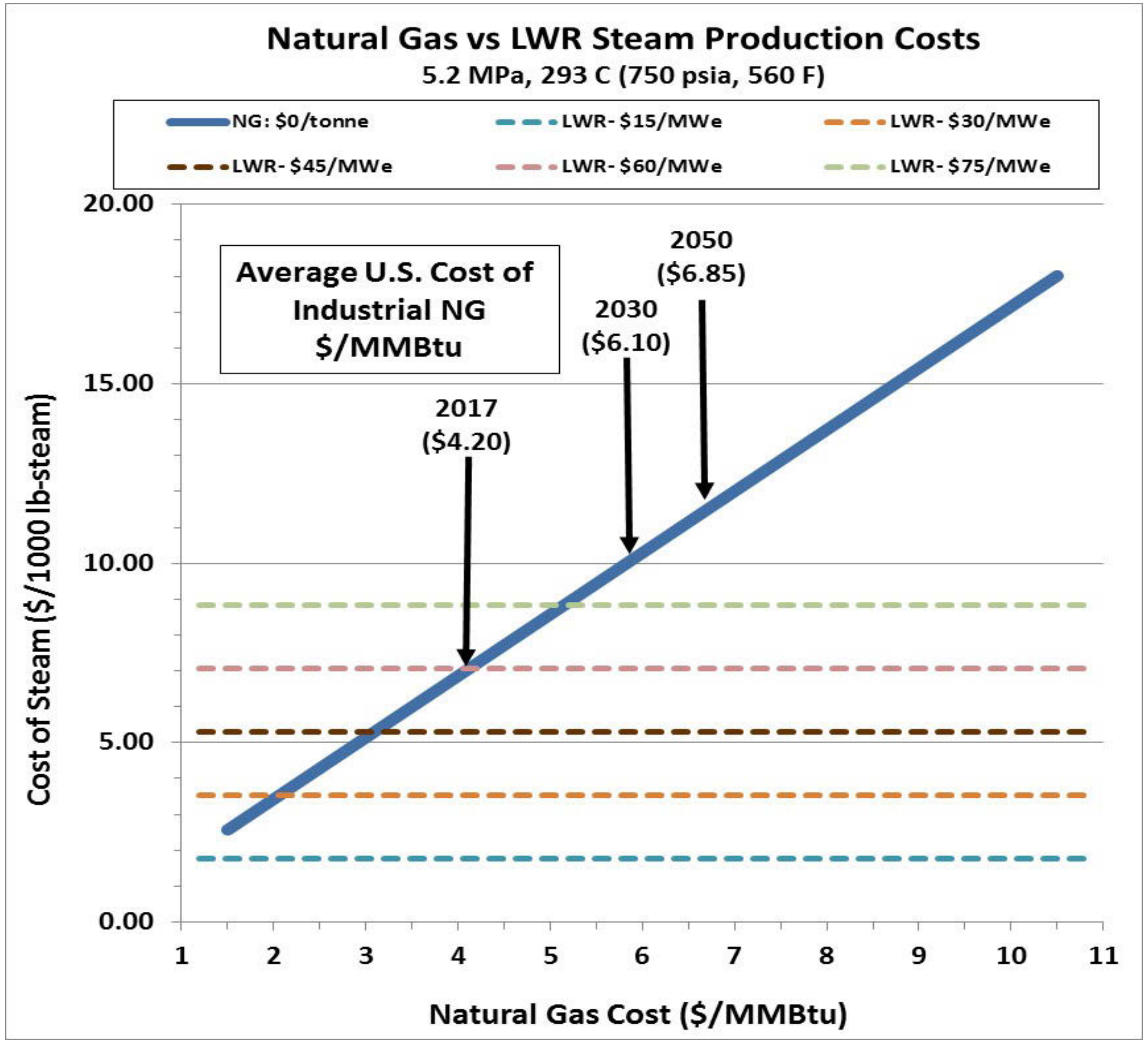


Conclusion #4:

- Higher capacity payments lead to more optimal configurations that provide grid support
- Meaning there is value for providing a generation guarantee
- 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

Thermal Energy May Be an Opportunity for Nuclear Energy



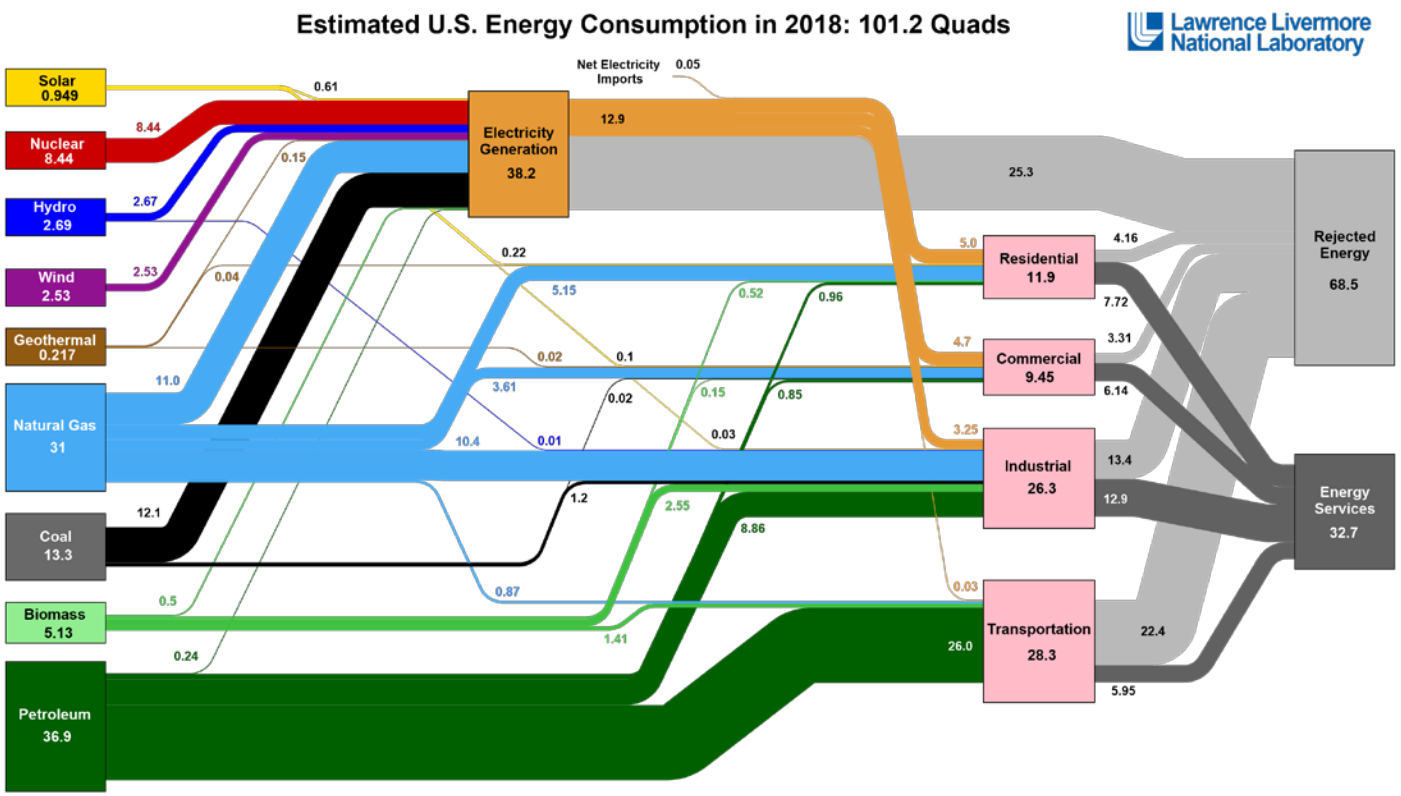
Conclusion #5:
Nuclear reactors may be competitive selling thermal energy

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

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.

The Future – Dependent Upon the Right Opportunities

1. Opportunities for nuclear energy as a thermal source



Source: LLNL March, 2019. Data is based on DOE/EIA MER (2018). If this information or a reproduction of it is used, credit must be given to the Lawrence Livermore National Laboratory and the Department of Energy, under whose auspices the work was performed. Distributed electricity represents only retail electricity sales and does not include self-generation. EIA reports consumption of renewable resources (i.e., hydro, wind, geothermal and solar) for electricity in BTU-equivalent values by assuming a typical fossil fuel plant heat rate. The efficiency of electricity production is calculated as the total retail electricity delivered divided by the primary energy input into electricity generation. End use efficiency is estimated as 65% for the residential sector, 65% for the commercial sector, 21% for the transportation sector and 49% for the industrial sector, which was updated in 2017 to reflect DOE's analysis of manufacturing. Totals may not equal sum of components due to independent rounding. LLNL-MI-410527

2. Roles for and market structures that enable “always-on” generation to provide capacity
3. Reduce capital costs for industrial and thermal applications to make them more flexible
4. Identify integrated hybrid thermal / electrical or fuel hybrid options

Finding the Right Niche: Small Modular Reactors

- Inherently safe designs
- Modular – lower capital cost
- Can provide thermal energy
- Can provide capacity

NuScale Reactor

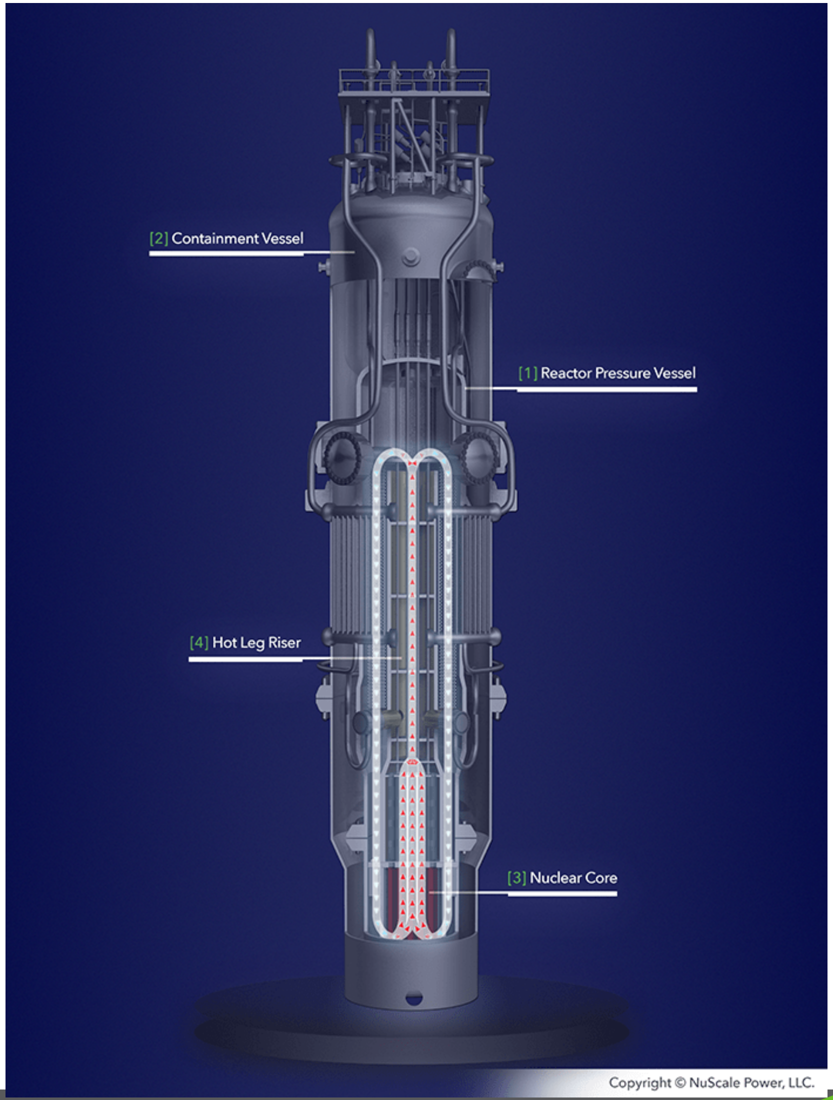
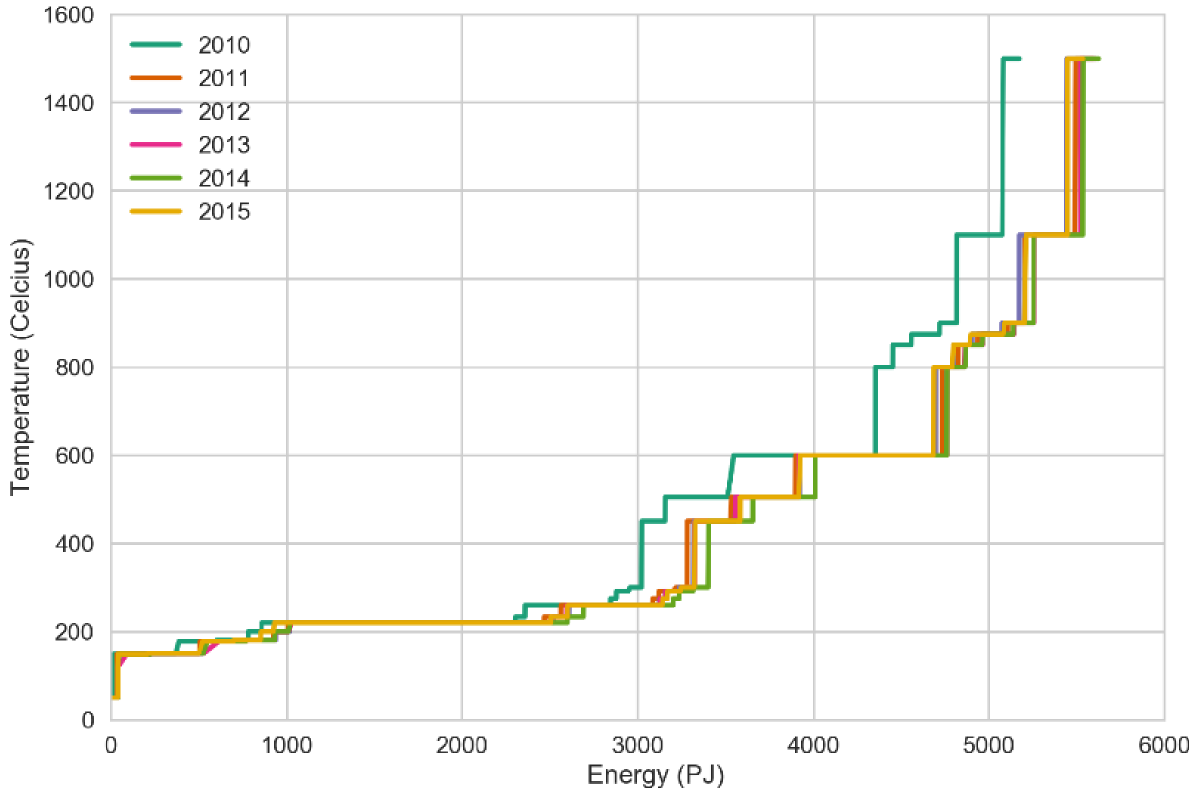


Image Source: https://www.nuscalepower.com/technology/design-innovations (June 19, 2019).

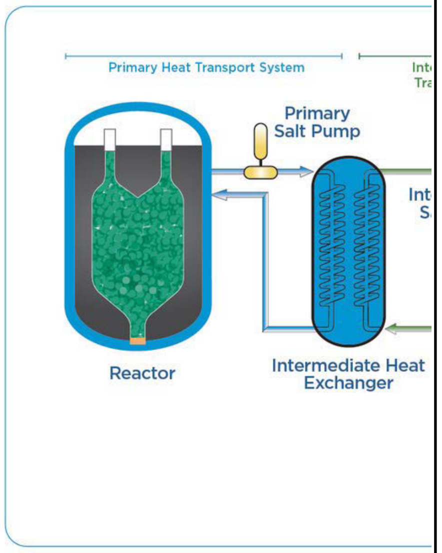
But Higher Temperatures are Needed for Many Applications



Source: Colin A. McMillan, Mark Ruth. "Using facility-level emissions data to estimate the technical potential of alternative thermal sources to meet industrial heat demand" *Applied Energy*, V. 239, (2019) p.1077-1090,

- Process heat consumes about 51% of U.S. industrial energy demand
- Low-carbon sources that meet quality requirements and are economic is a key challenge
- In addition, higher temperatures increase electricity generation efficiency

Additional Designs are Also Under Development

	NuScale	X-Energy	Terrestrial Energy	Kairos
Coolant Type	Light-water	Gas-Cooled Pebble Bed	Molten Salt	Fluoride Sodium
Temperature	300°C	850°C	700-800°C	500-550°C
Reactor Size	50 MWe	75 MWe	195 MWe	TBD
Plant Size	600 MWe	300 MWe	195 MWe	TBD
Information provided by Jordan Cox - NREL (June 19, 2019)			 The Replaceable IMSR® Core-unit.	

Potential Show Stoppers for Nuclear Power

- Public safety concerns
- Regulation and its costs
- Waste disposal
- Non-proliferation challenges

Image Source: https://www.energy.gov/ne/articles/nuclear-101-how-does-nuclear-reactor-work (June 19, 2019).

International Cooperation

NICE Future
Nuclear Innovation: Clean Energy Future

An Initiative of the Clean Energy Ministerial

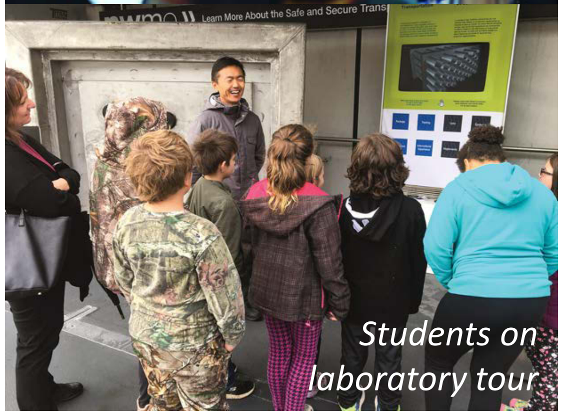

Research facility


Researcher in laboratory

Focus Areas

1. Exploring innovative applications for advanced nuclear systems both electric and non-electric.	2. Engaging policy makers and stakeholders regarding energy choices for the future.
3. Pooling experience on economics, including valuation, markets structure, and ability to finance.	4. Communicating nuclear energy's role in clean integrated energy systems and developing the nuclear workforce of the future.


Panel discussion


Students on laboratory tour

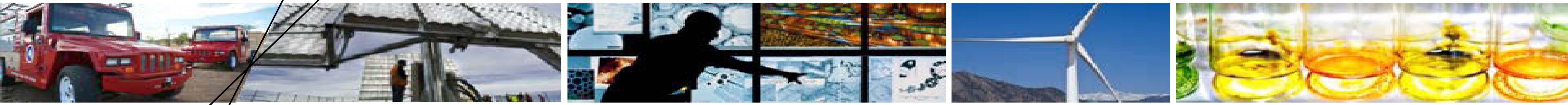
Does Nuclear Have a Role in a Renewable Energy World?

Yes, providing

- Costs are reduced
- Applications are expanded to utilize technologies' strengths (i.e., thermal energy)
- Firm, fixed electricity generation capacity is valued
- Show-stoppers are not overwhelming

Nuclear and Renewable systems power a data center as part of Third Way's "Nuclear Reimagined" series. https://www.thirdway.org/blog/nuclear-reimagined

Joint Institute for Strategic Energy Analysis



Thank you!

mark.ruth@nrel.gov
www.nrel.gov

NREL/PR-6A20-74220

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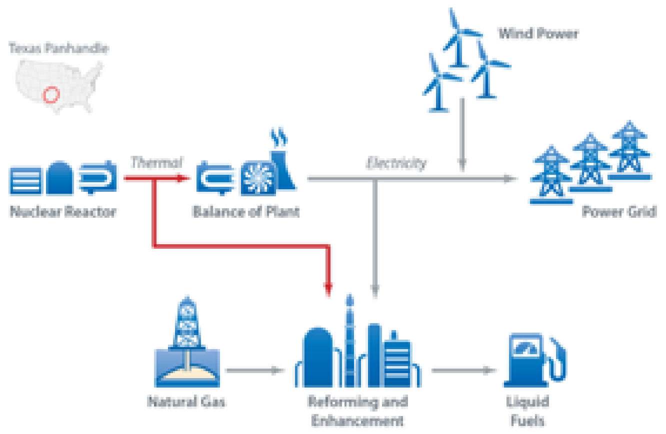
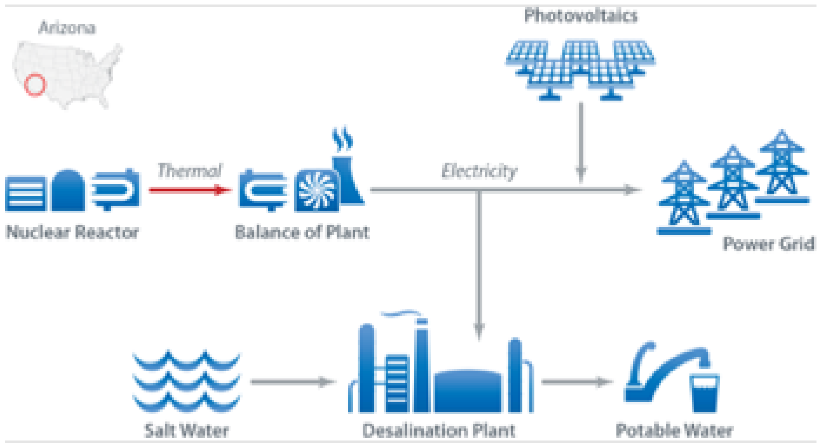
Use Cases Analyzed

Liquid Transportation Fuels



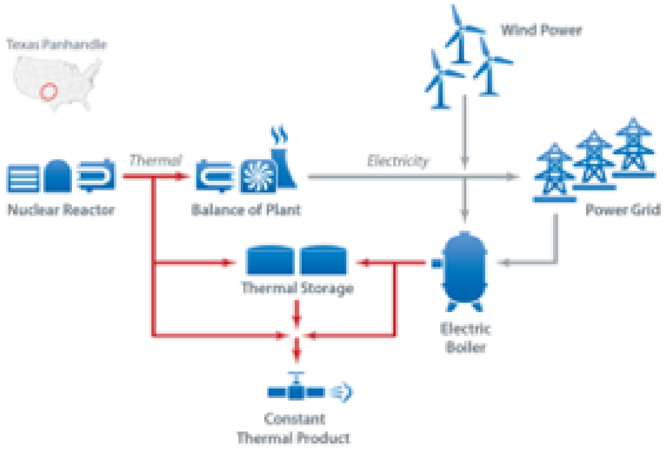
Thermal interconnection

Reverse Osmosis Desalination



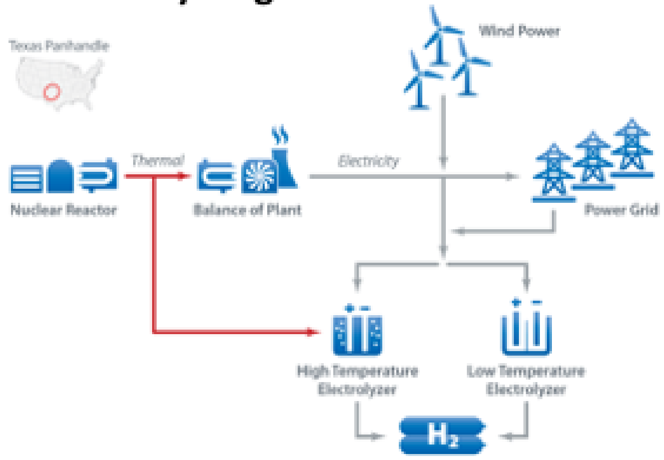
Electrical interconnection
No purchase of grid electricity

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

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

Capacity Payment

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

Capital & Operating Costs

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

Other Costs

Additional Financial Analysis

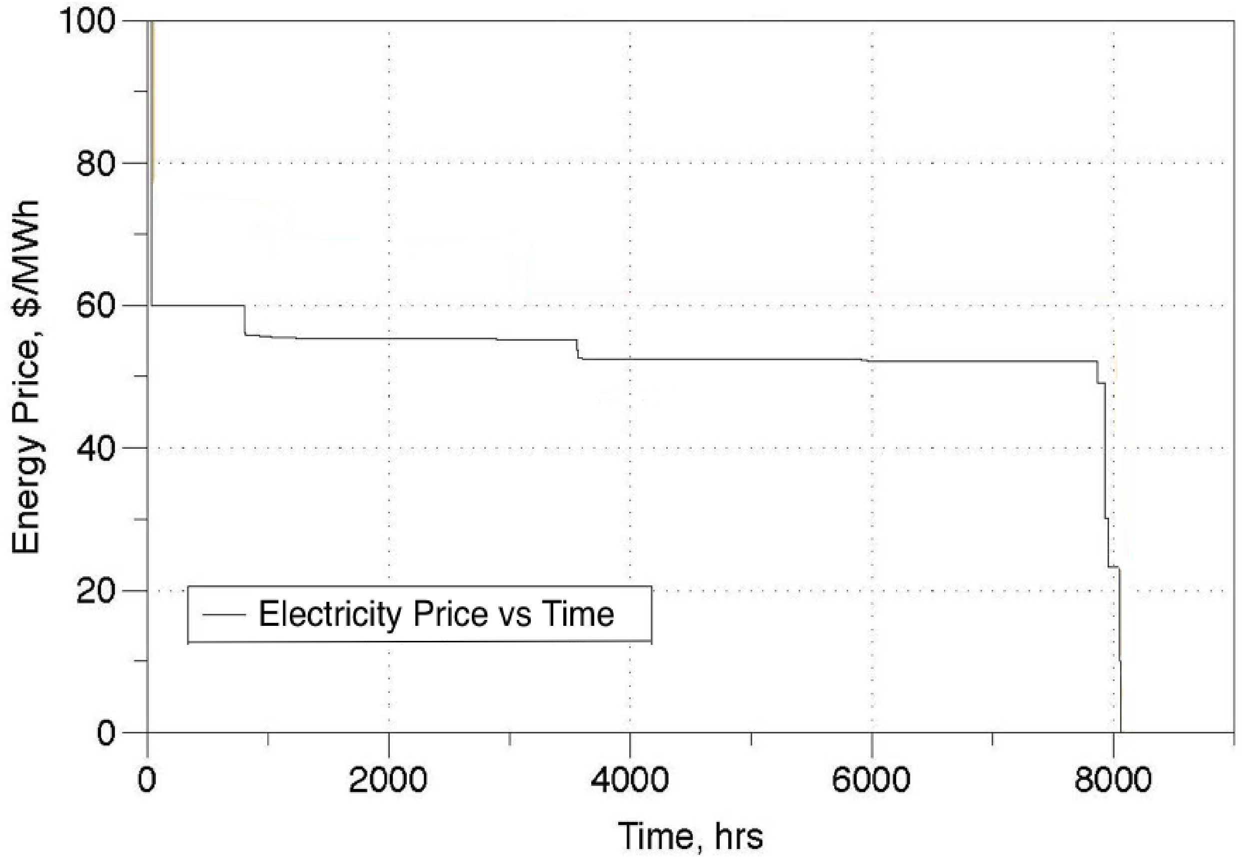
10% after tax IRR on 100% equity financing. 25 year analysis life. 35% tax rate. 3% inflation rate.

Electricity Prices

Developed and used generation mixes that cause volatile electricity prices

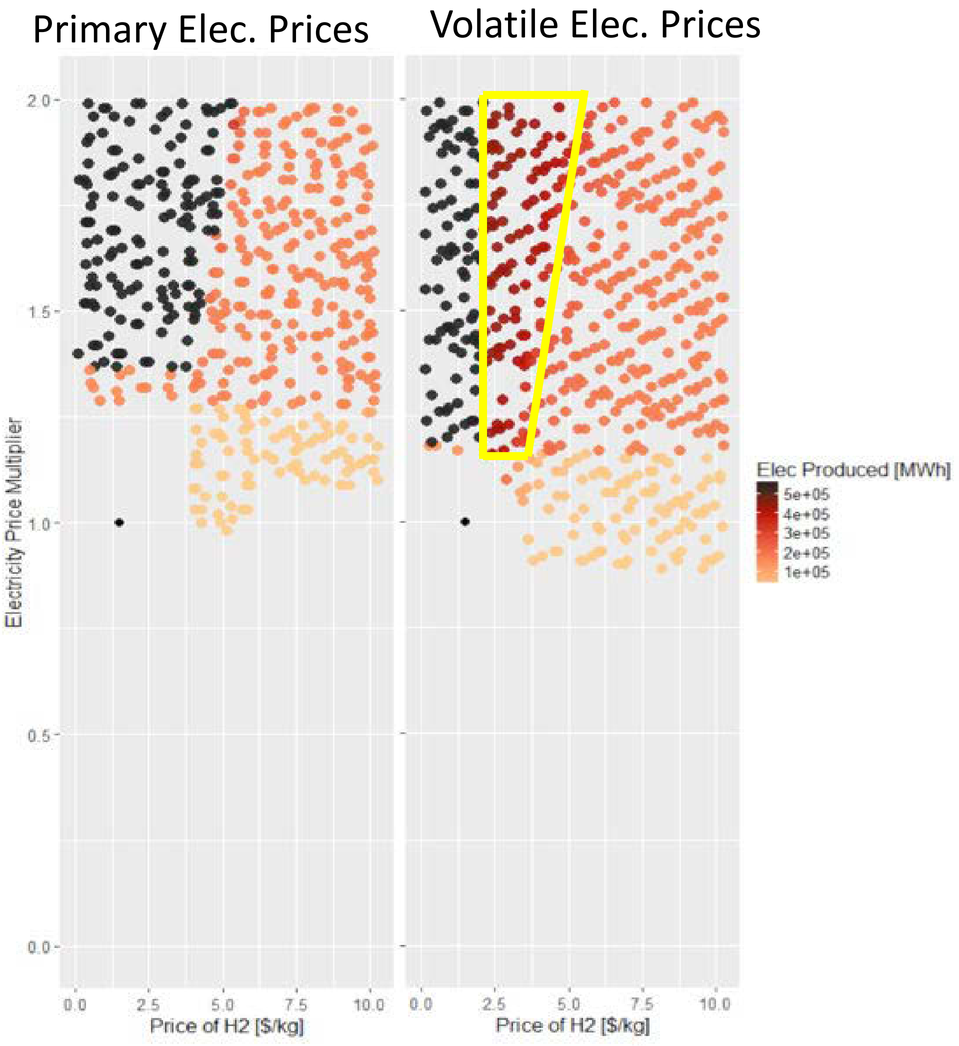
Price Set	Primary	Arizona	Volatile
Wind generation percentage	21%	11%	8.6%
PV generation percentage	20%	22%	37%
Hours at $0/MWh annually	704	700	2,246

Energy Price Duration Curve for Texas Use Cases

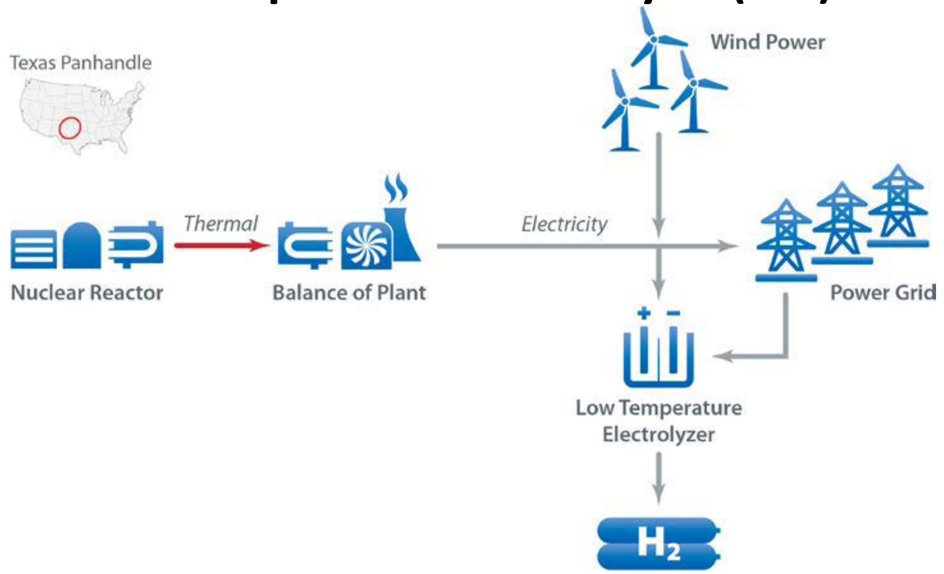


Ruth, Mark, Spitsen, Paul, Boardman, Richard, Bragg-Sitton, Richard "Opportunities and Challenges for Nuclear-Renewable Hybrid Energy Systems" Proceedings from IAEA Technical Meeting on Nuclear-Renewable Hybrid Energy Systems for Decarbonized Energy Production and Cogeneration. October 2018.

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



Low Temperature Electrolysis (LTE)



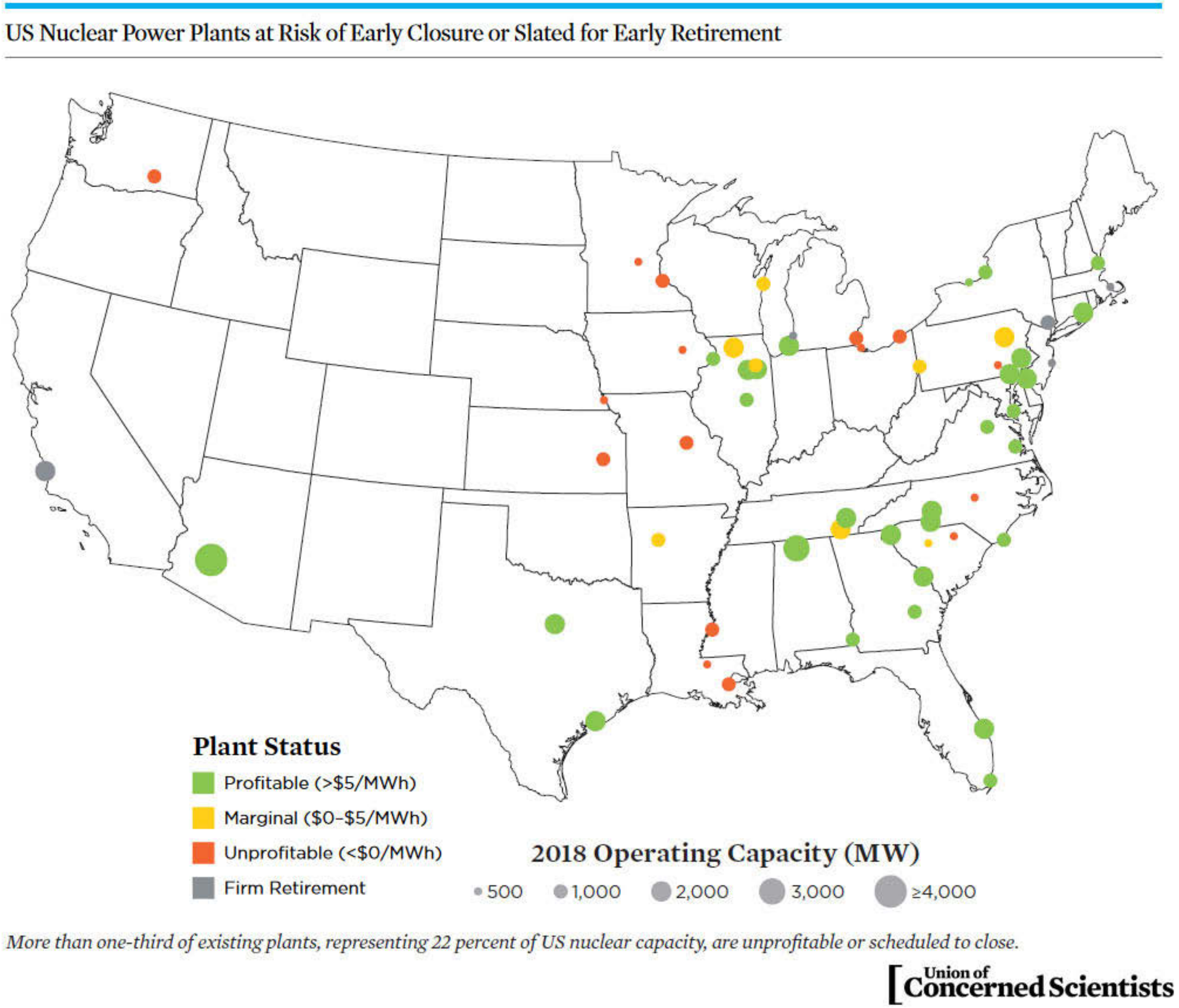
- N-R HES can produce electricity when price is high and industrial product when electricity price is low as shown in the yellow polygon
- High and volatile energy prices necessary to realize the benefits of arbitrage

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

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. Higher capacity payments lead to more optimal configurations that provide grid support but a sufficient industrial product price is still critical
5. Nuclear reactors may be competitive selling thermal energy providing a thermal energy market exists and they can access that market

Electricity Price Impacts on Nuclear Power Plants



Thus, many have minimal profit margins and others are shutting down.

What is a possible solution?

Flexible Generation

Source: **Union of Concerned Scientists,** "The Nuclear Dilemma" https://www.ucsusa.org/nuclear-power/cost-nuclear-power/retirements (June 19, 2019).