JISEA Joint Institute for Strategic Energy Analysis

# Technoeconomic Analysis of Nuclear-Renewable Hybrid Energy Systems – Opportunities, Learnings, and Challenges

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Advanced Clean Energy Summit – Denver, CO

NREL NATIONAL RENEWABLE ENERGY LABORATORY
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- 327-acre campus in Golden & 305-acre National Wind Technology Center 13 miles north
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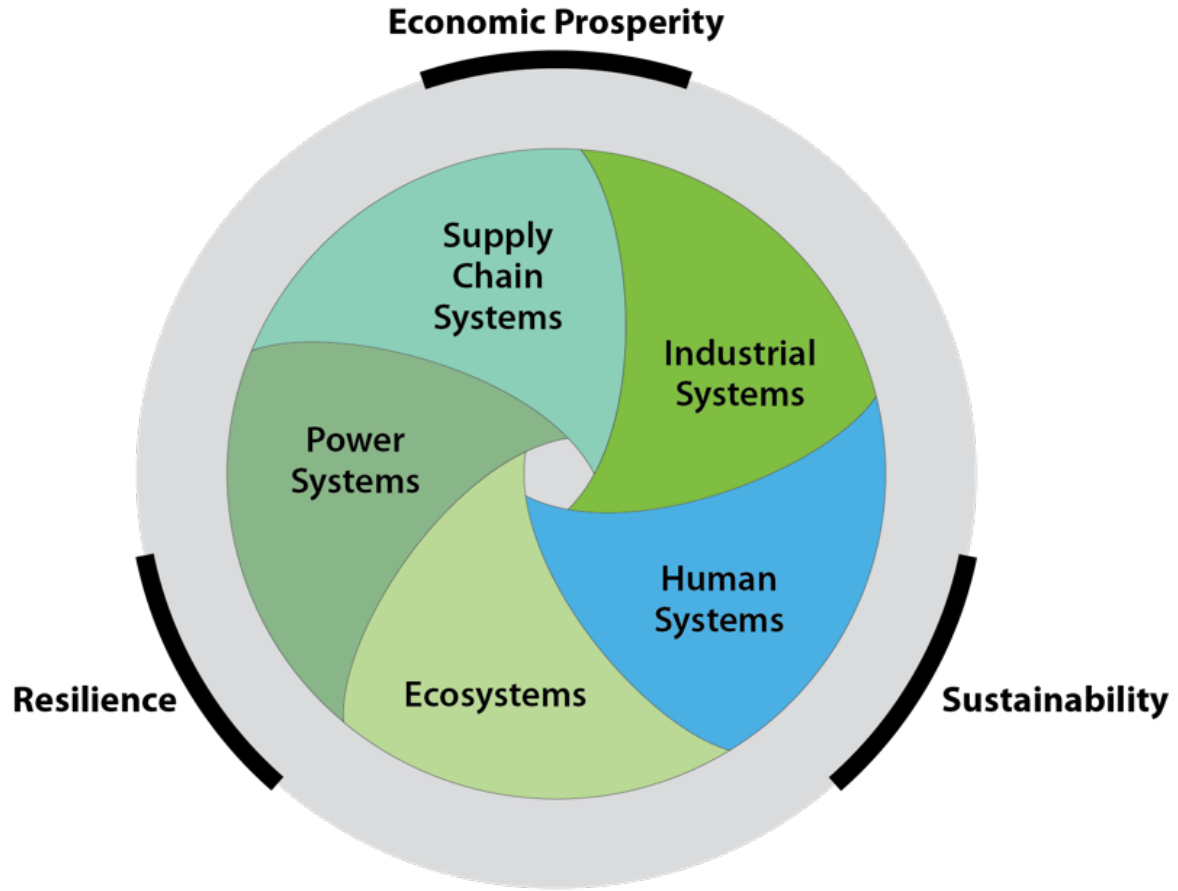
# JISEA

## Joint Institute for Strategic Energy Analysis

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

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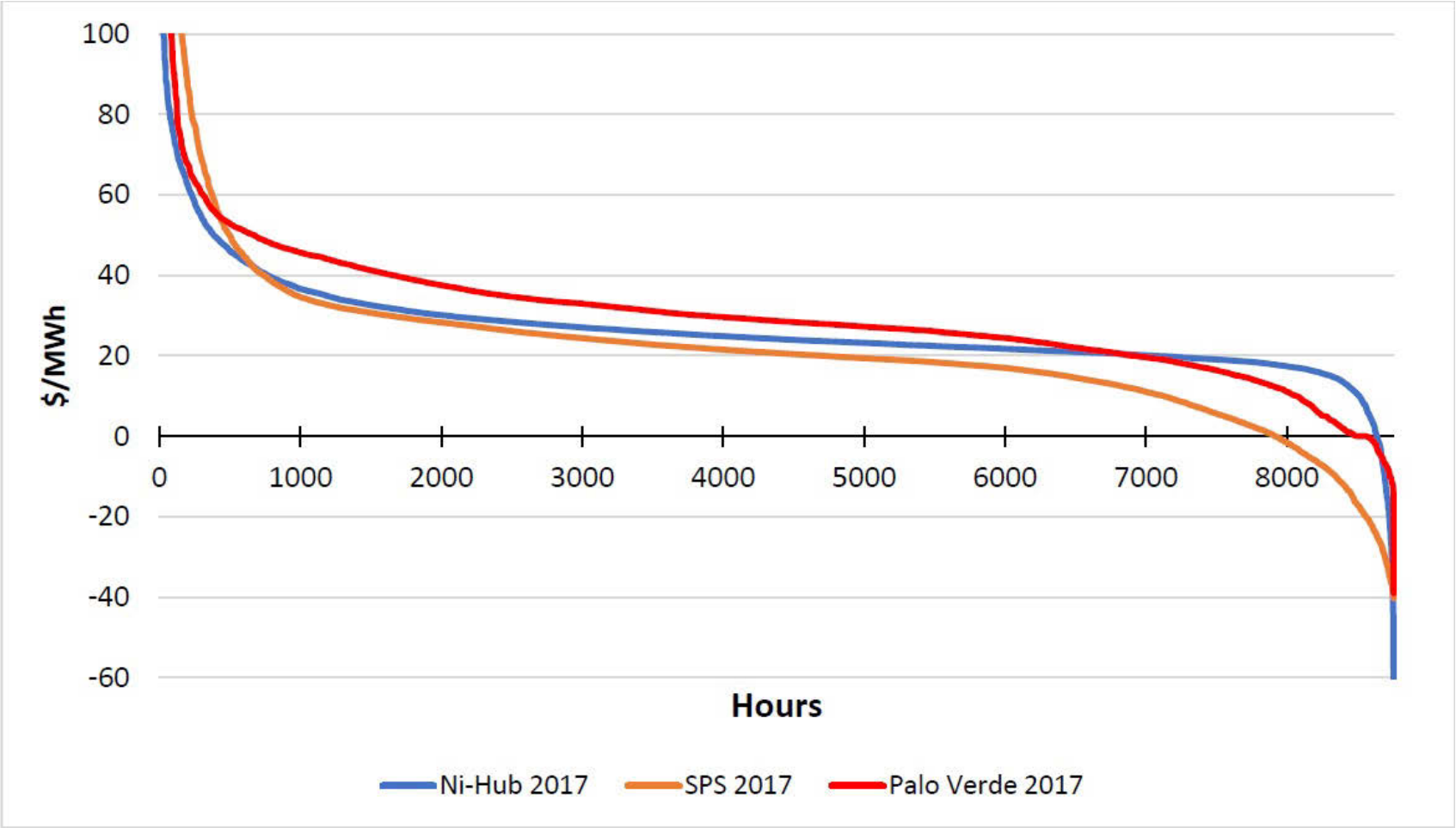
# Reduced and Volatile Electricity Prices




**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

# Reduced and Volatile Electricity Prices are a Challenge

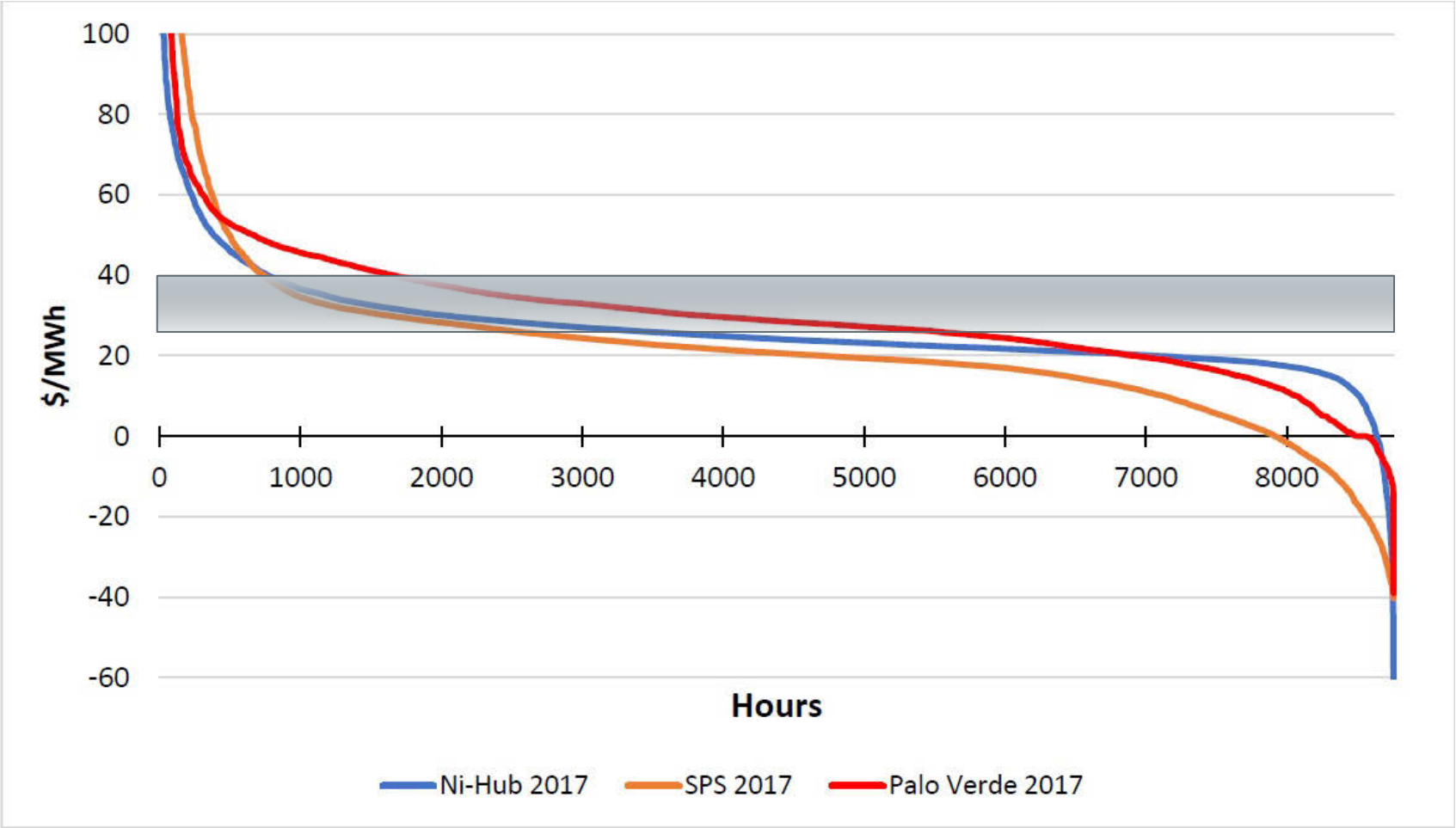



Figure created by NREL (Daniel Levie) based on publicly available price data

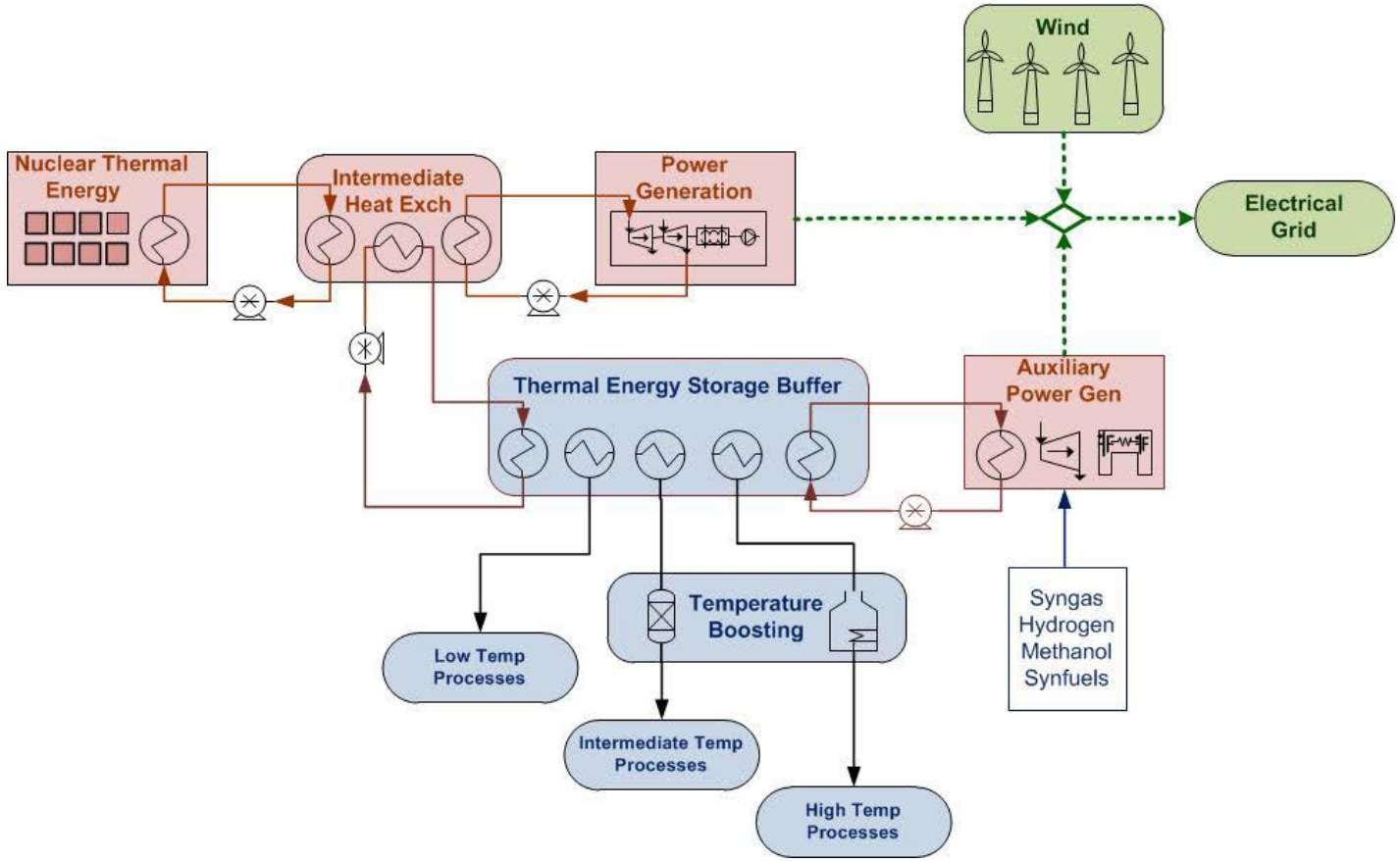
**Some nuclear power plants may sell energy at a loss 35% or more of the hours in a year depending upon their technology, scale, location, and market.**

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

# 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)

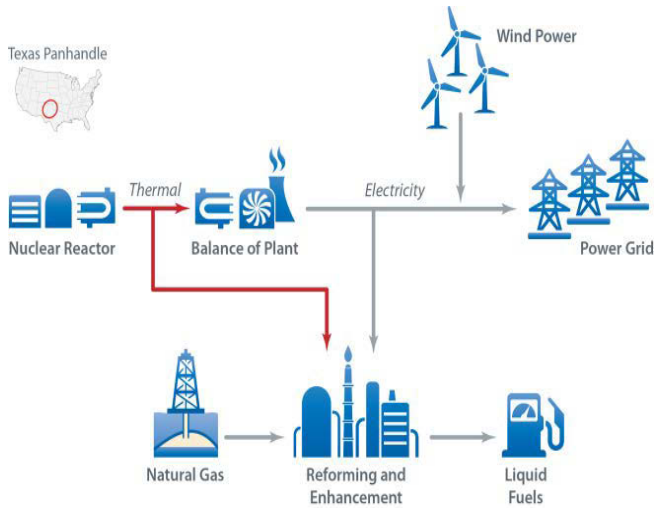
# JISEA's Analysis

- Financial (Technoeconomic) 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

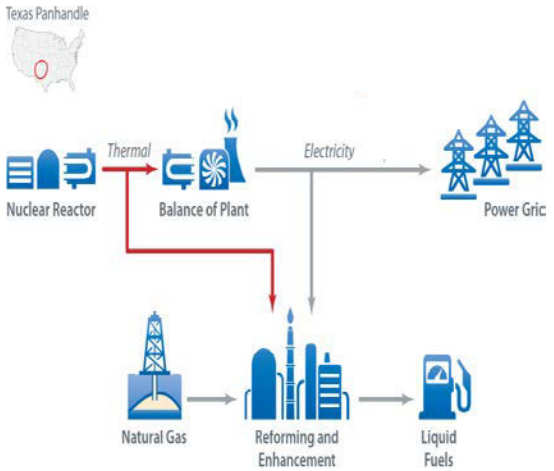
# Analysis Methodology

Identify optimal configurations and
internal dispatch under various product prices

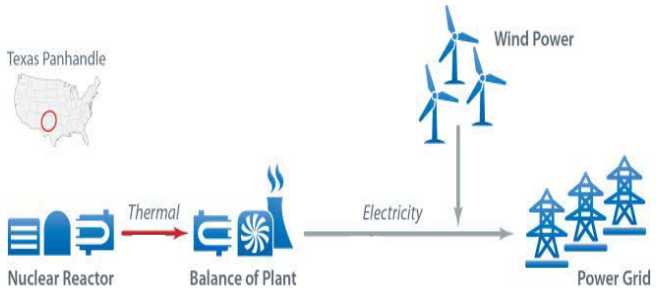
Full Configuration




Partial Configuration




Another Partial Configuration



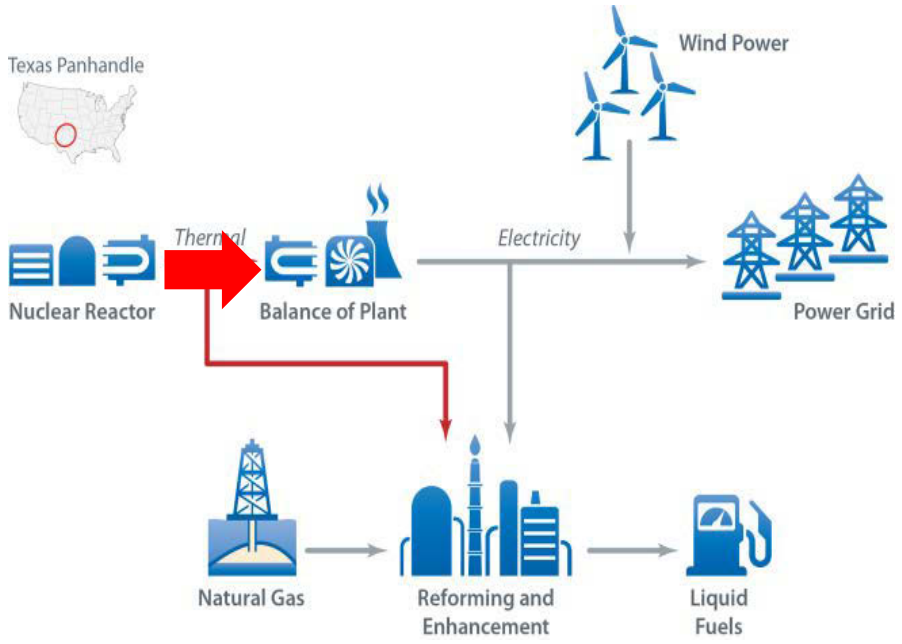

Other configurations: (1) nuclear-generated electricity only and (2) wind only

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

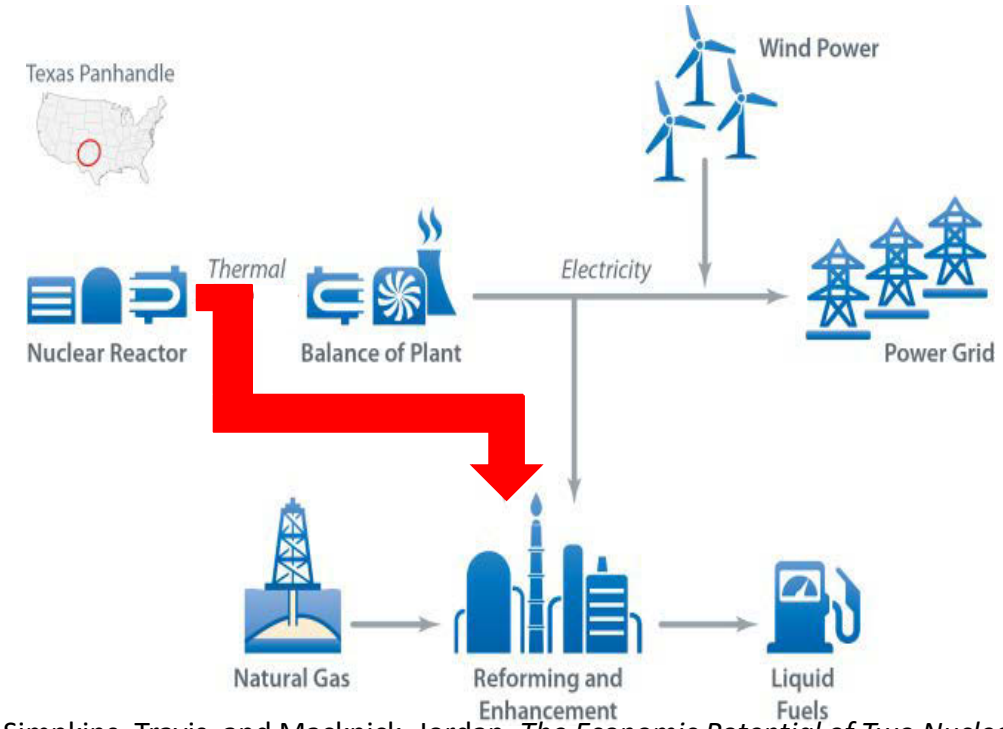
# Analysis Methodology

Identify optimal configurations and
internal dispatch under various product prices

## One Dispatch Option

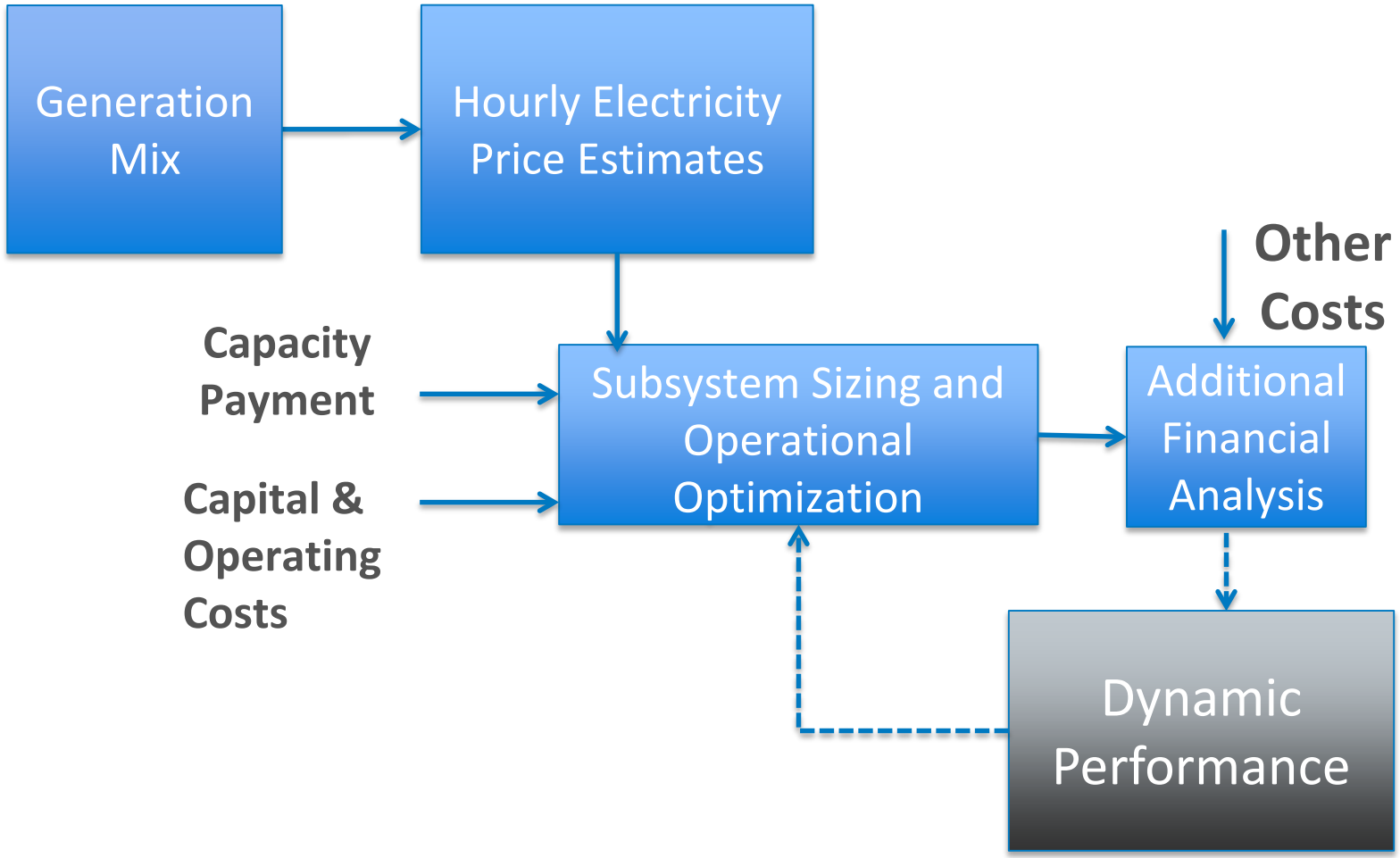



## Second Dispatch Option




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

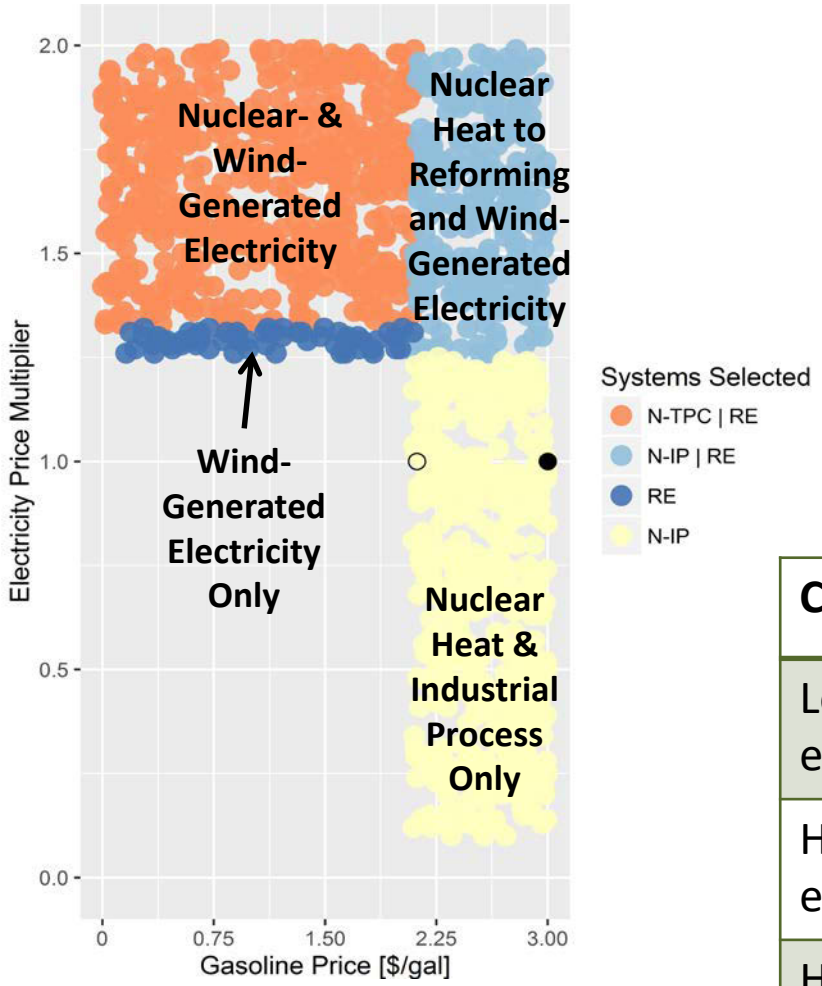



## Industrial Systems Analyzed

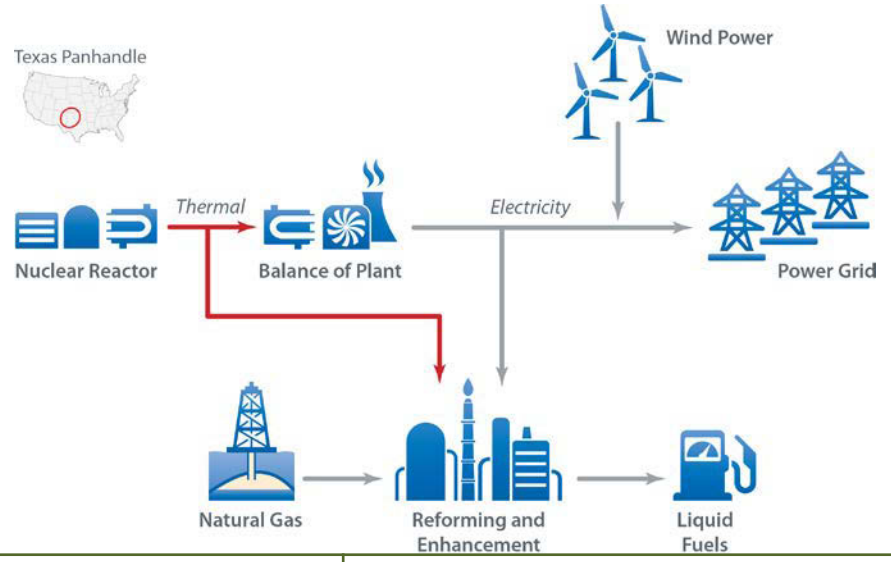
- Natural gas to liquid fuels
- Reverse osmosis desalination
- Thermal energy to a power park
  - With and without storage
- Hydrogen production
  - Via low-temperature electrolysis (LTE)
  - Via high-temperature electrolysis (HTE)

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

# Optimal Configurations Liquid Fuels Use Case



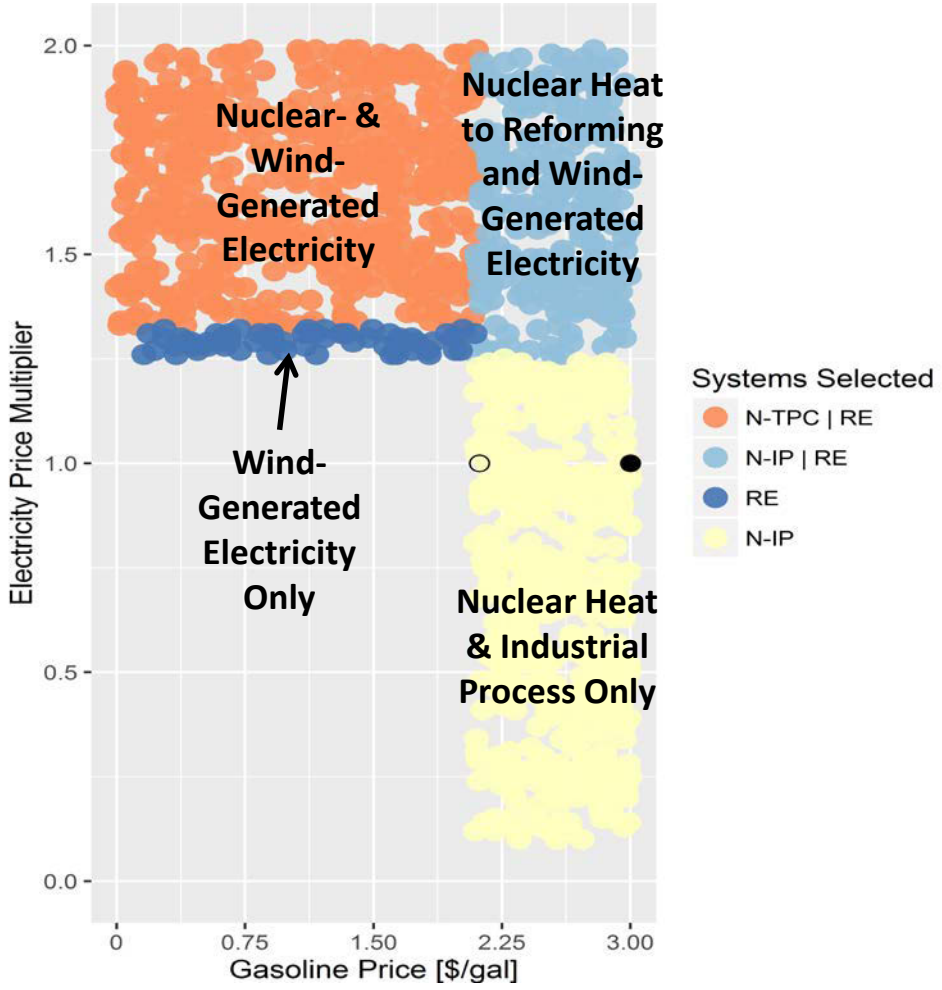

N-TPC: Nuclear reactor and thermal
N-IP: Nuclear reactor and industrial process
RE: Renewable electricity generation




| 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
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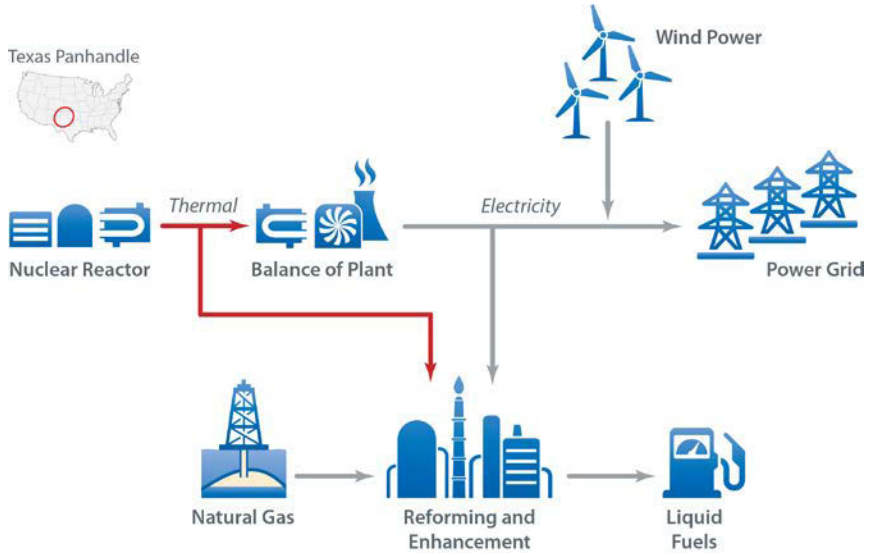



**Conclusion #1:**

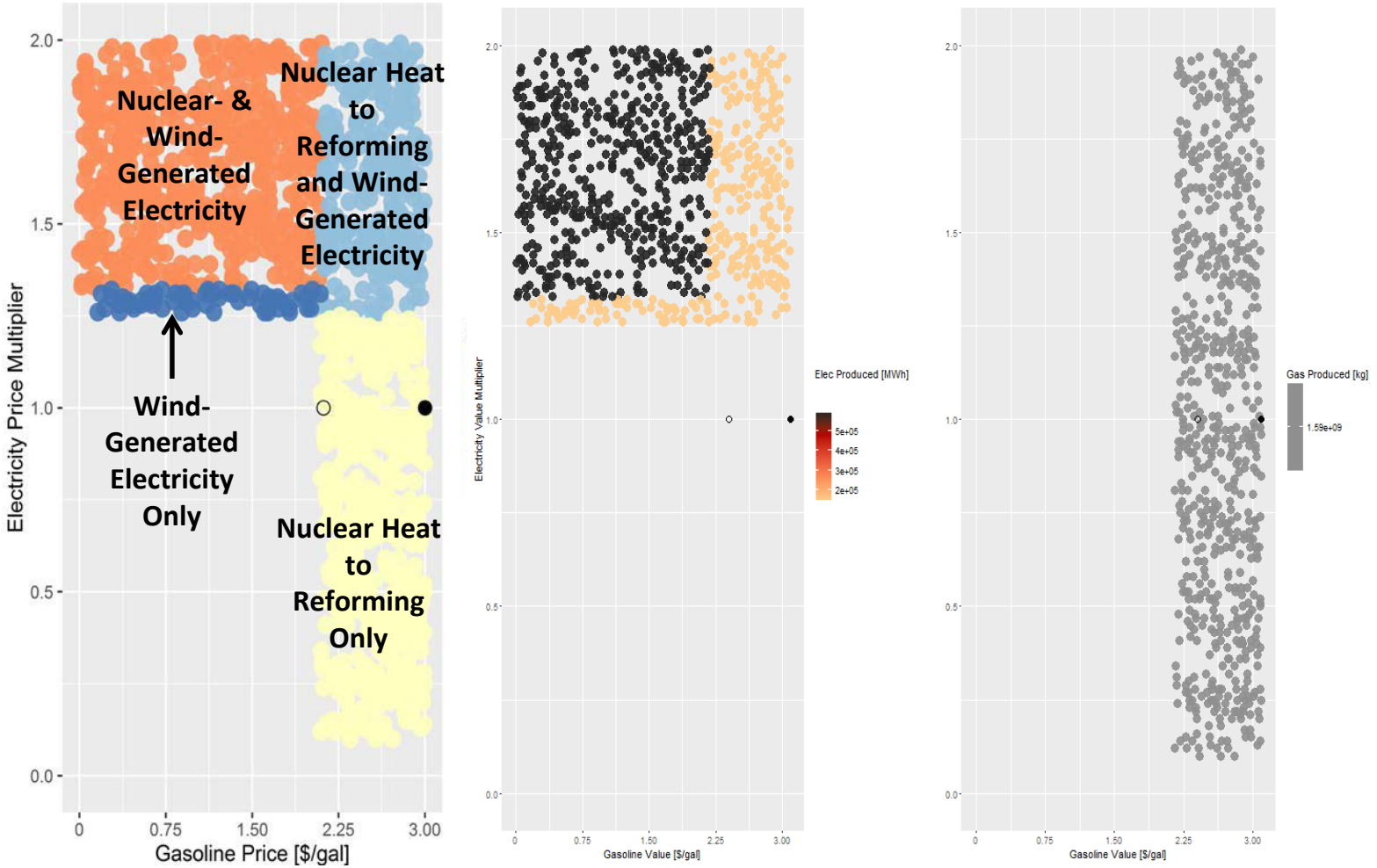
Under our analytical method and most of our assumptions, the primary driver for whether a subsystem is included in the optimal configuration is whether it would be profitable independently

**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

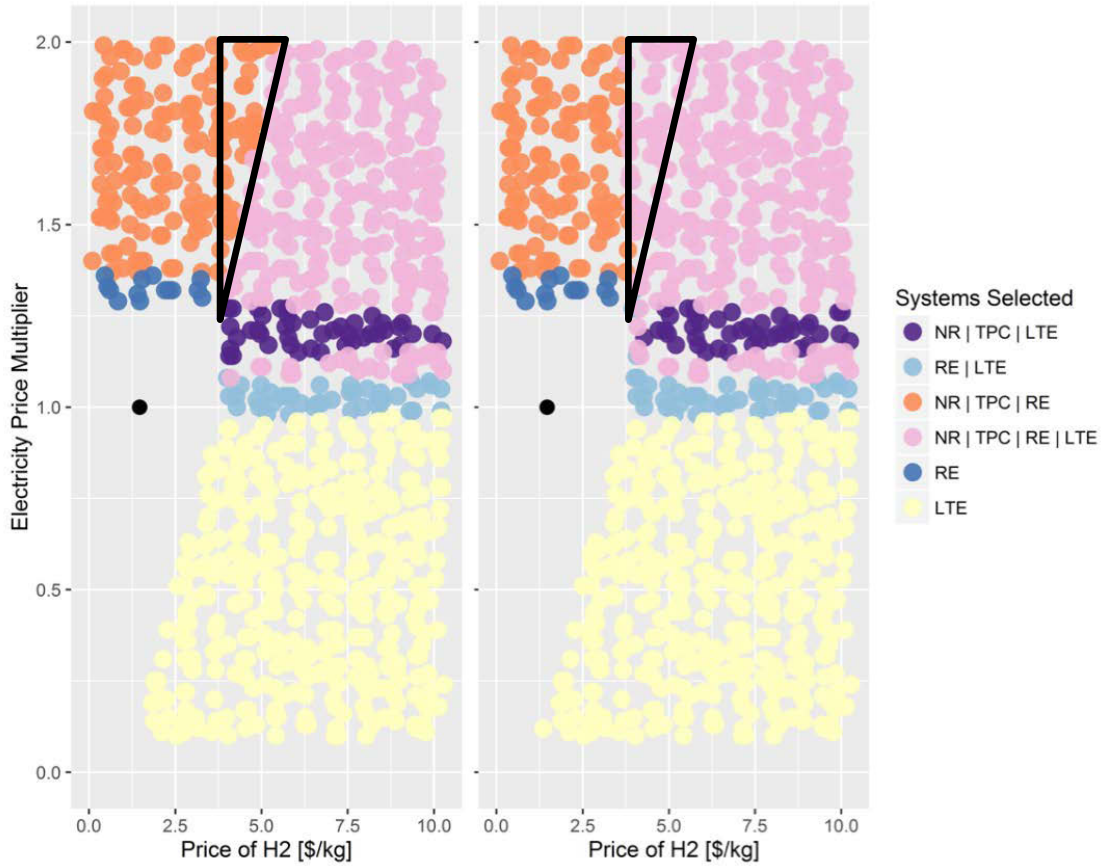
**Conclusion #2:**
Industrial processes usually maximize profitability by operating the maximum number of hours possible in a year

**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

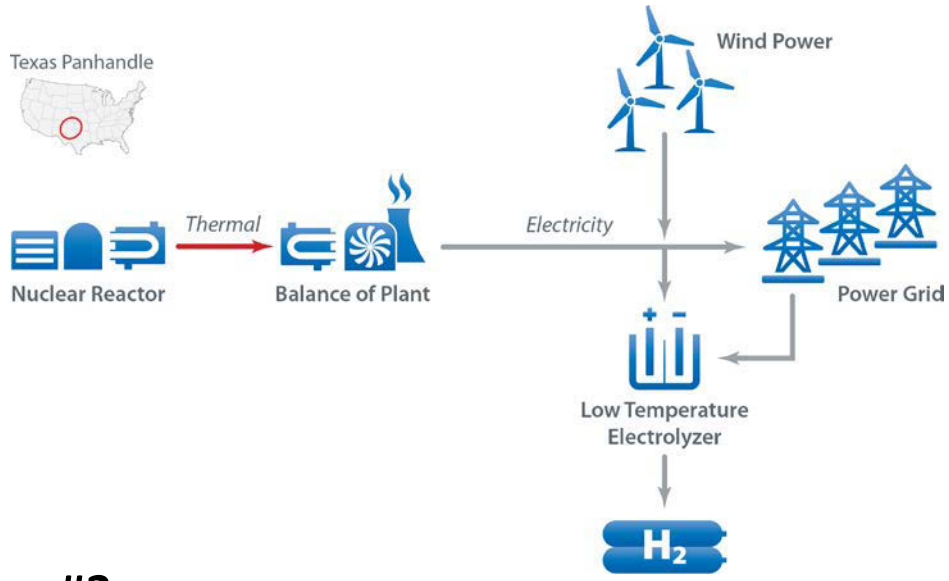
# Flexibility Benefits N-R HESs with Lower Capital Cost Industrial Processes

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)**



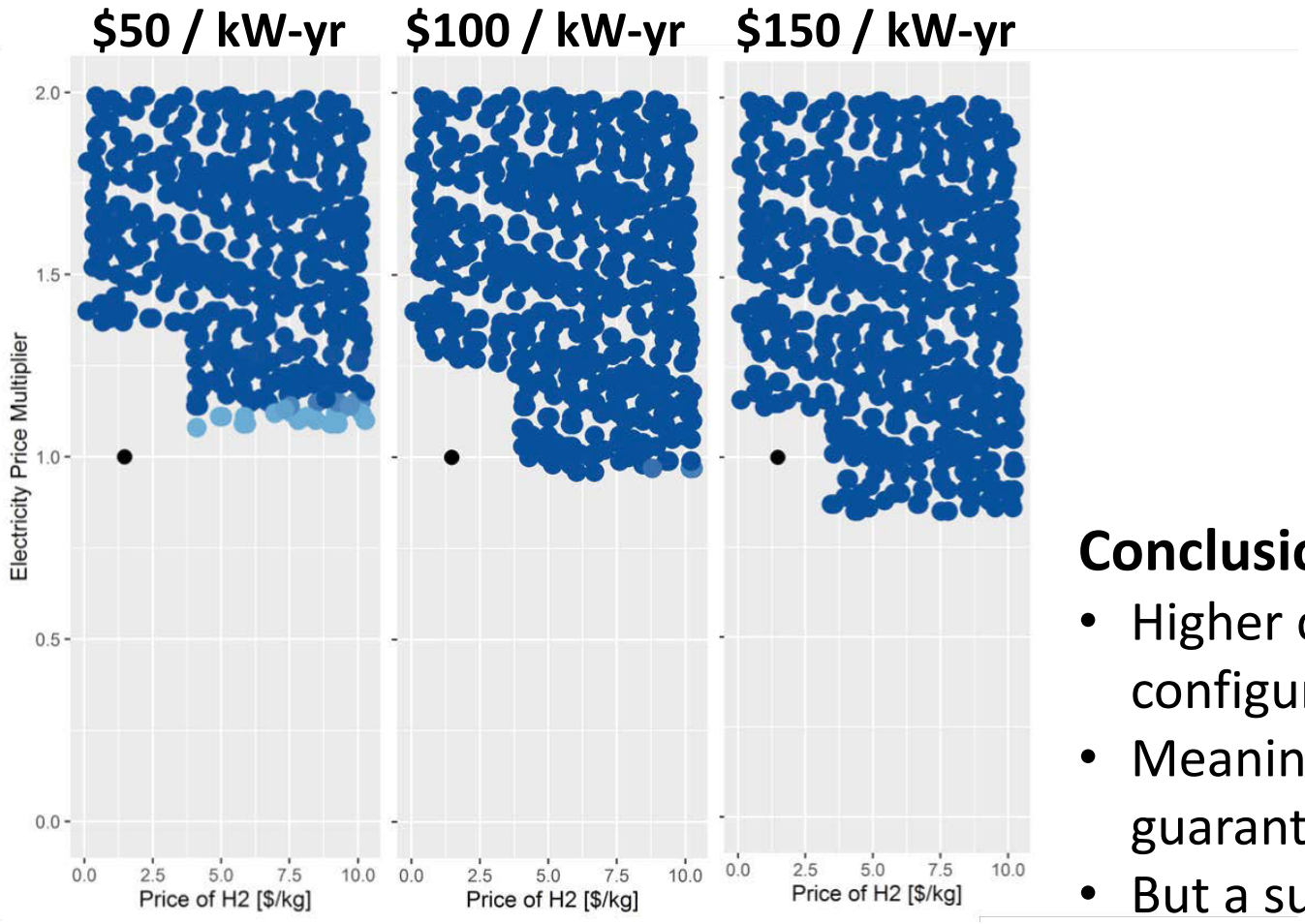

**Conclusion #3:**

- 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

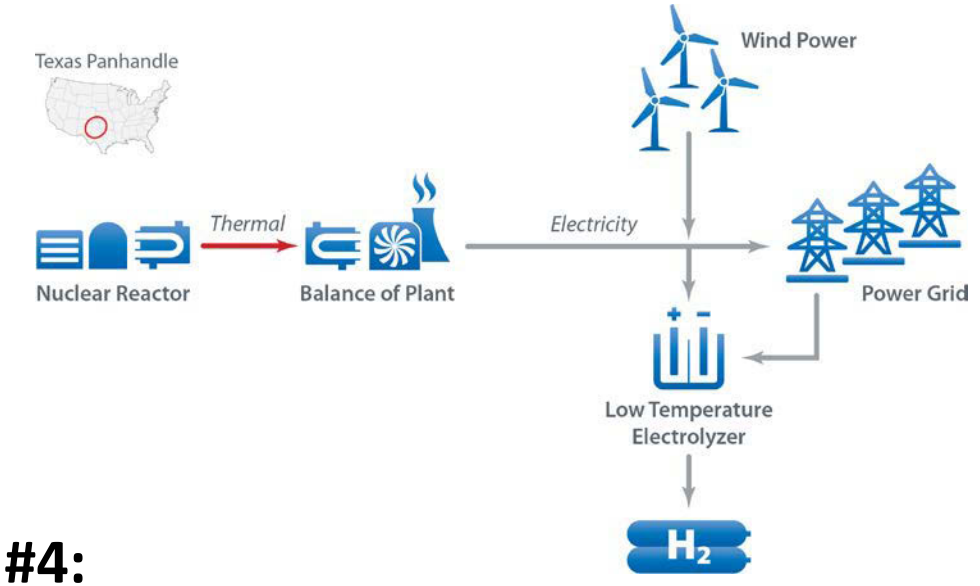
Source: Ruth, Mark, Cutler, Dylan, Flores-Espino, Francisco, and Stark, Greg. *The Economic Potential of Nuclear-Renewable Hybrid Energy Systems Producing Hydrogen* (2017). NREL/TP-6A50-66764. http://www.nrel.gov/docs/fy17osti/66764.pdf

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

## Capacity Payment




## Low Temperature Electrolysis (LTE)

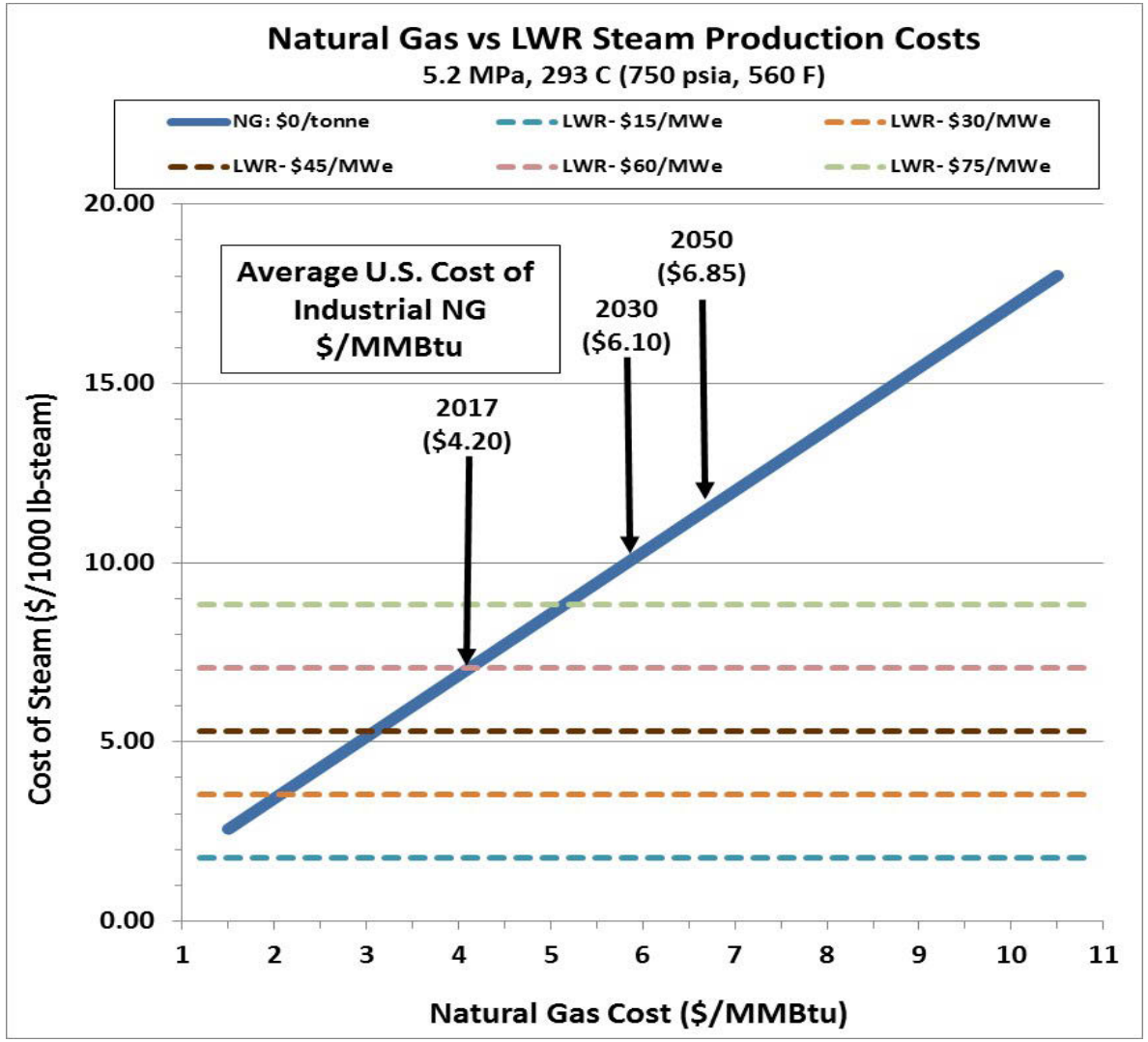



## Conclusion #4:

- 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.

# 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

# International Cooperation

NICE Future
Nuclear Innovation: Clean Energy Future

An Initiative of the Clean Energy Ministerial


*Research facility*


*Researcher in laboratory*

## Focus Areas

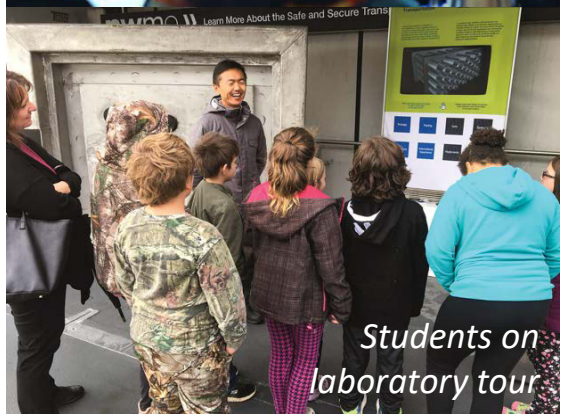
1. Exploring innovative applications for advanced nuclear systems both electric and non-electric.

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*

# Thank you!

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## For more information:

Ruth, Mark, Paul Spitsen, and Richard Boardman. 2019. Opportunities and Challenges for Nuclear-Renewable Hybrid Energy Systems: Preprint. Golden, CO: National Renewable Energy Laboratory. NREL/CP-6A20-72004. https://www.nrel.gov/docs/fy19osti/72004.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

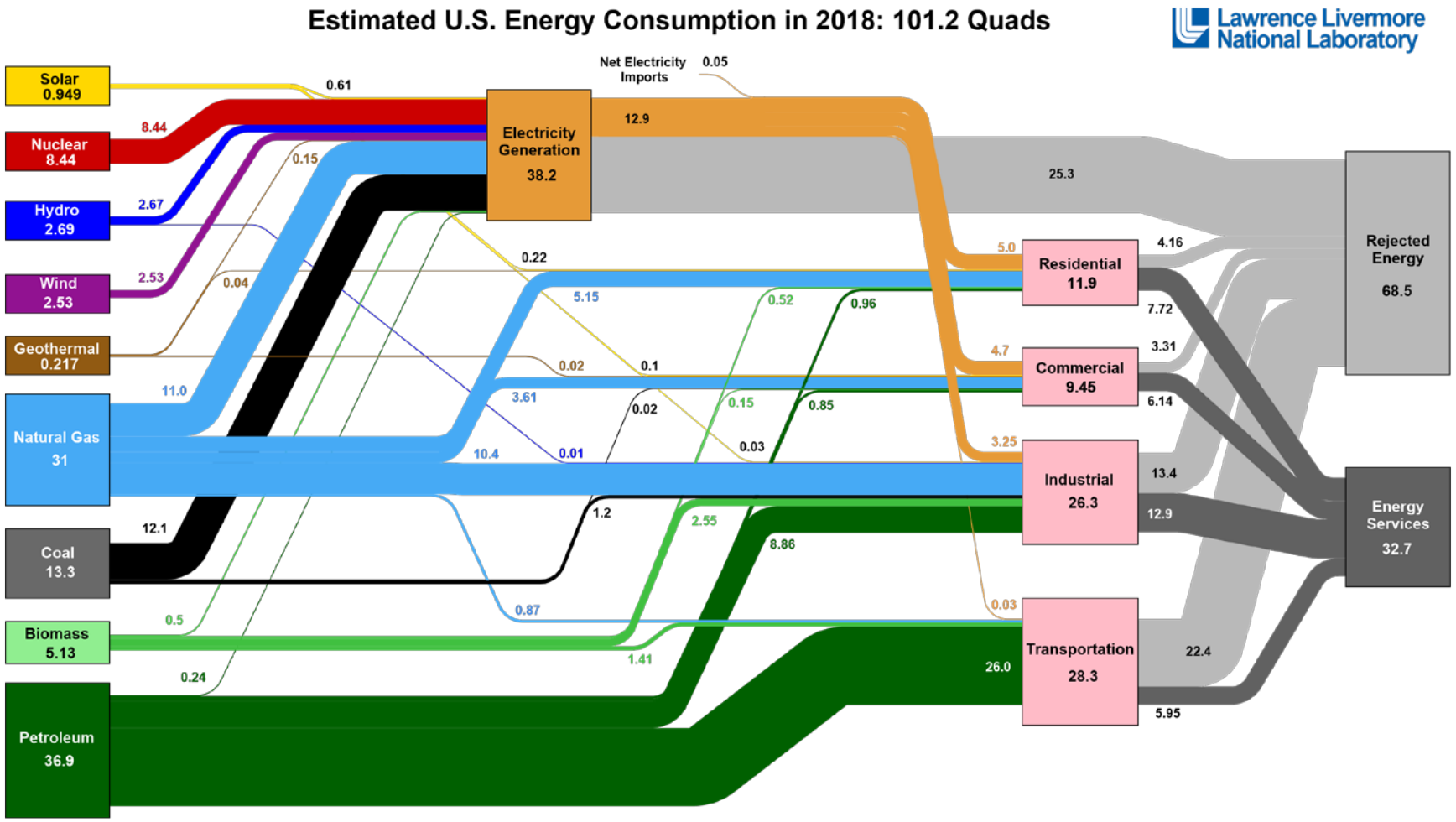
Ruth, Mark, Cutler, Dylan, Flores-Espino, Francisco, Stark, Greg, and Jenkin, Thomas. *The Economic Potential of Three Nuclear-Renewable Hybrid Energy Systems Providing Thermal Energy to Industry* (2016). NREL/TP-6A50-66745. http://www.nrel.gov/docs/fy17osti/66745.pdf

Bragg-Sitton, Shannon, Boardman, Richard, Ruth, Mark, and Lyons, Peter. *International Workshop to Explore Synergies between Nuclear and Renewable Energy Sources as a Key Component in Developing Pathways to Decarbonization of the Energy Sector* (2016). INL/EXT-16-39701. https://inldigitallibrary.inl.gov/sites/sti/sti/7246953.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

Mark F. Ruth, Owen R. Zinaman, Mark Antkowiak, Richard D. Boardman, Robert S. Cherry, Morgan D. Bazilian, "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)

# Nuclear's Role in Today's Energy System



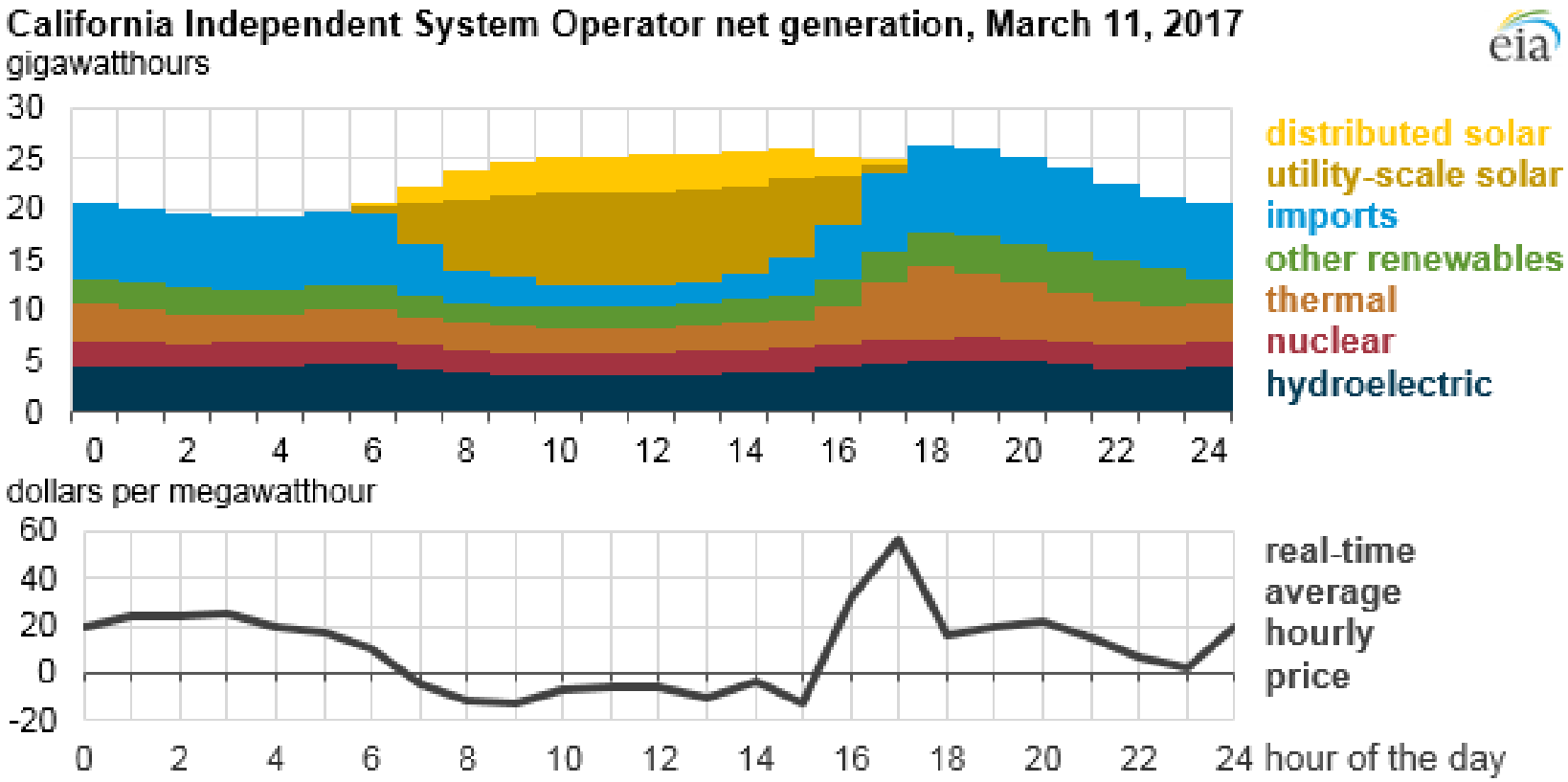

Source: LLNL March, 2019. Data is based on DOE/EIA MER (2018). If this information or a reproduction of it is used, credit must be given to the Lawrence Livermore National Laboratory and the Department of Energy, under whose auspices the work was performed. Distributed electricity represents only retail 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

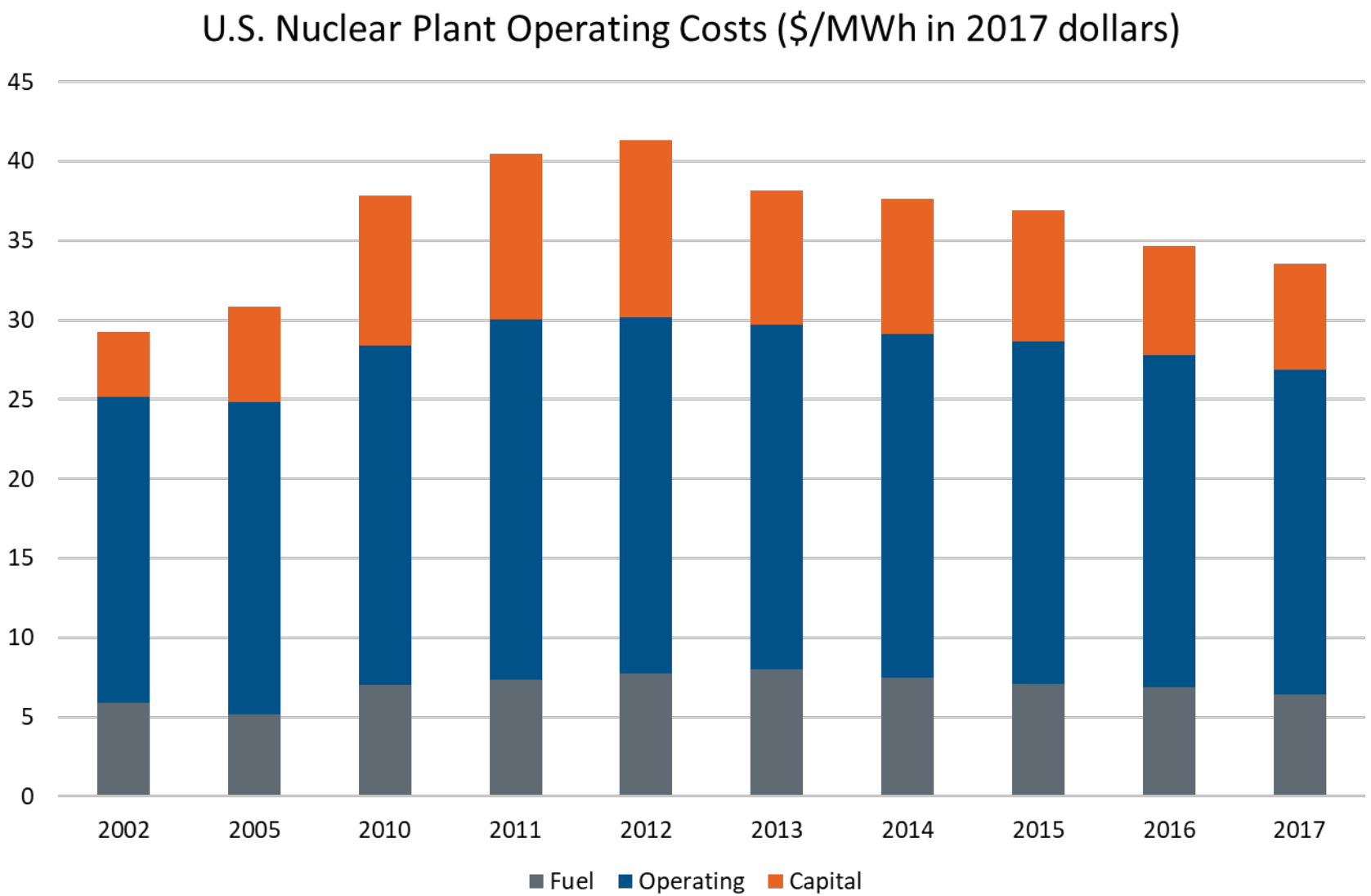



Source: **U.S. Energy Information Administration,** "Rising Solar Generation in California Coincides with Negative Wholesale Electricity Prices," EIA, Today in Energy, https://www.eia.gov/todayinenergy/detail.php?id=30692#tab4 (Apr. 7, 2017).

**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.**

# Operating Costs of Nuclear Power Plants



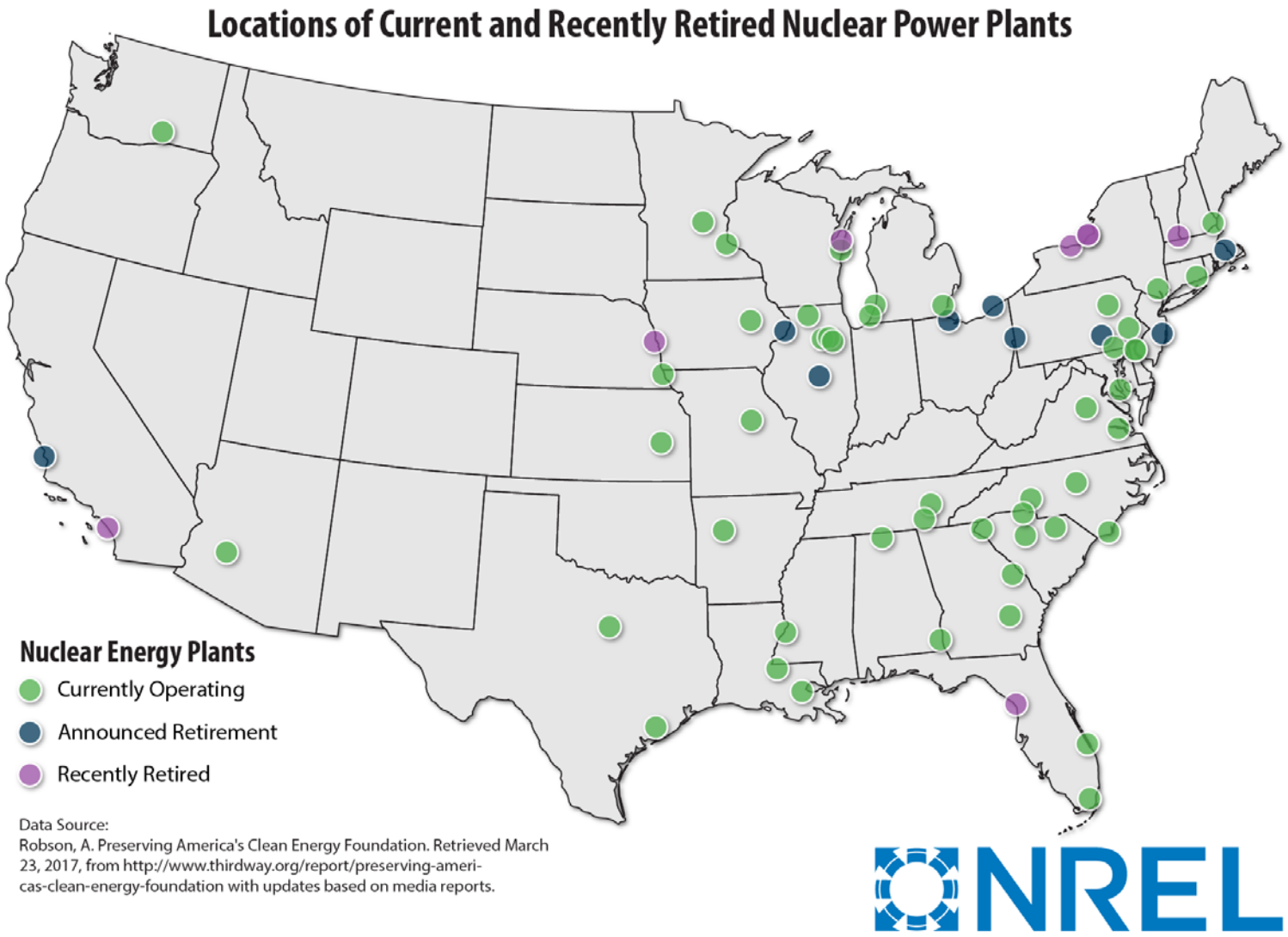

**Operating costs of nuclear plants are not negligible.**

**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).

# Electricity Price Impacts on Nuclear Power Plants



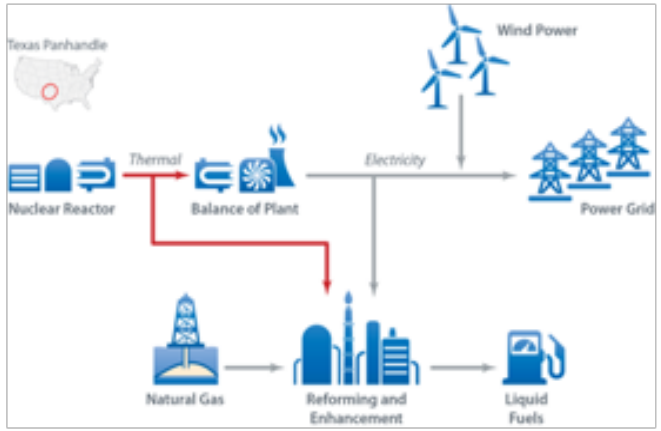

**Thus, many have minimal profit margins and others are shutting down. New nuclear power plants are unlikely to be built.**

**What is a possible solution?**

**Flexible Generation**

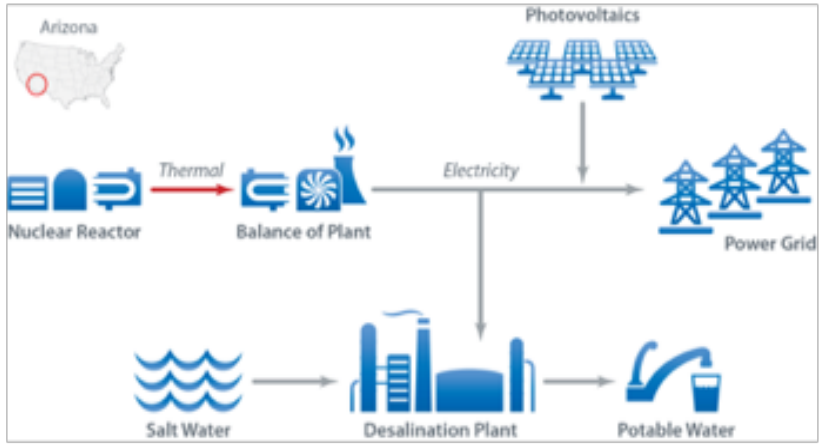
# Use Cases Analyzed

## Liquid Transportation Fuels



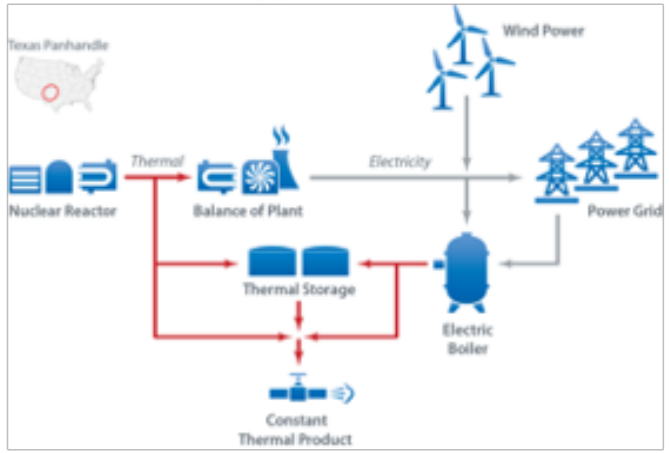

Thermal interconnection

## Reverse Osmosis Desalination



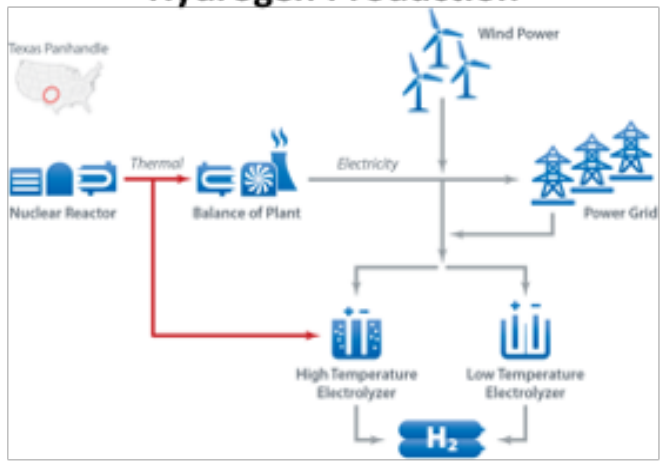

Electrical interconnection
No purchase of grid electricity

## Thermal Energy in an Industrial Park




Thermal interconnection (primarily)
Possible purchase of grid electricity

## Hydrogen Production

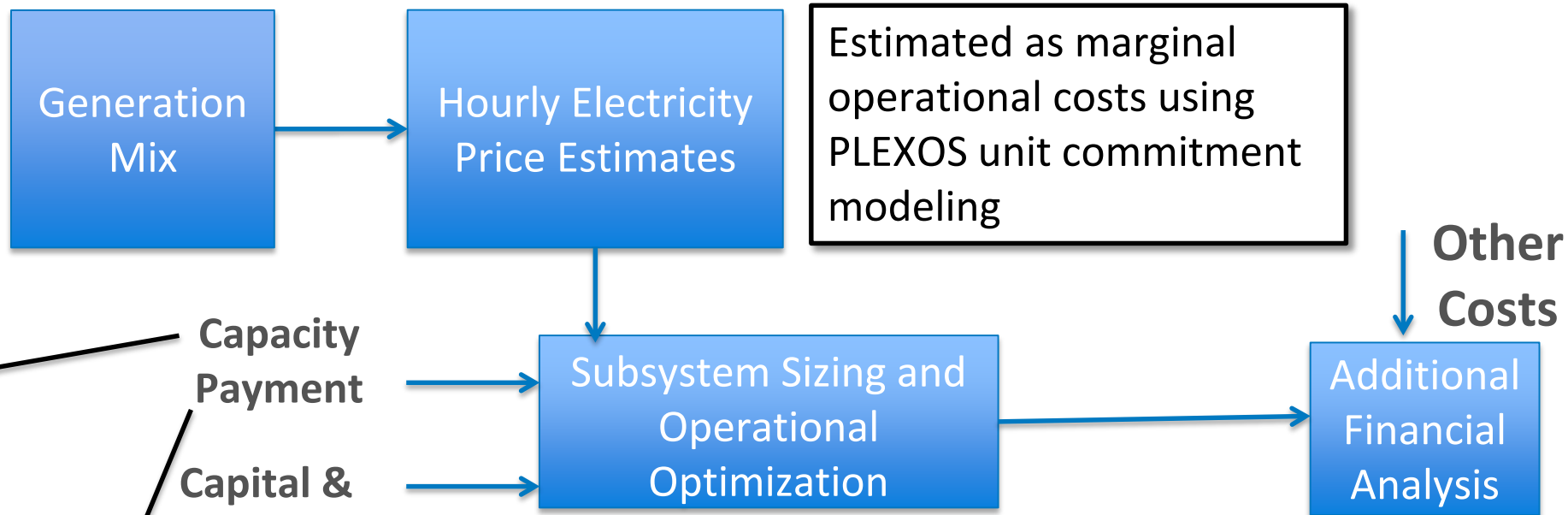



Electrical interconnection
Thermal interconnection for high temperature electrolysis.
Possible purchase of grid electricity

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




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

Used REopt to identify optimal configurations and internal dispatch

Maximum sizes for all subsystems set to 50 MWe equivalent

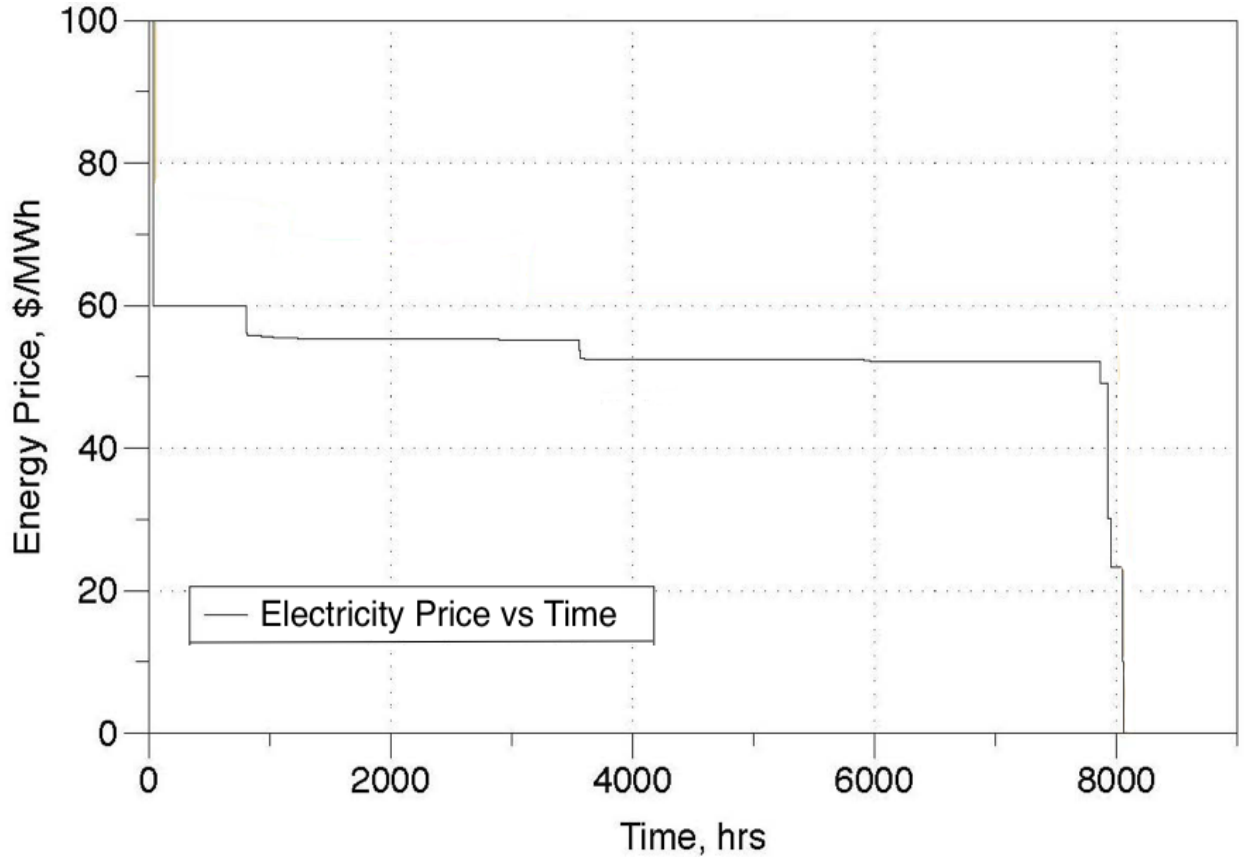
10% after tax IRR on 100% equity financing. 25 year analysis life. 35% tax rate. 3% inflation rate.

# Electricity Prices

Developed and used generation mixes that cause volatile electricity prices

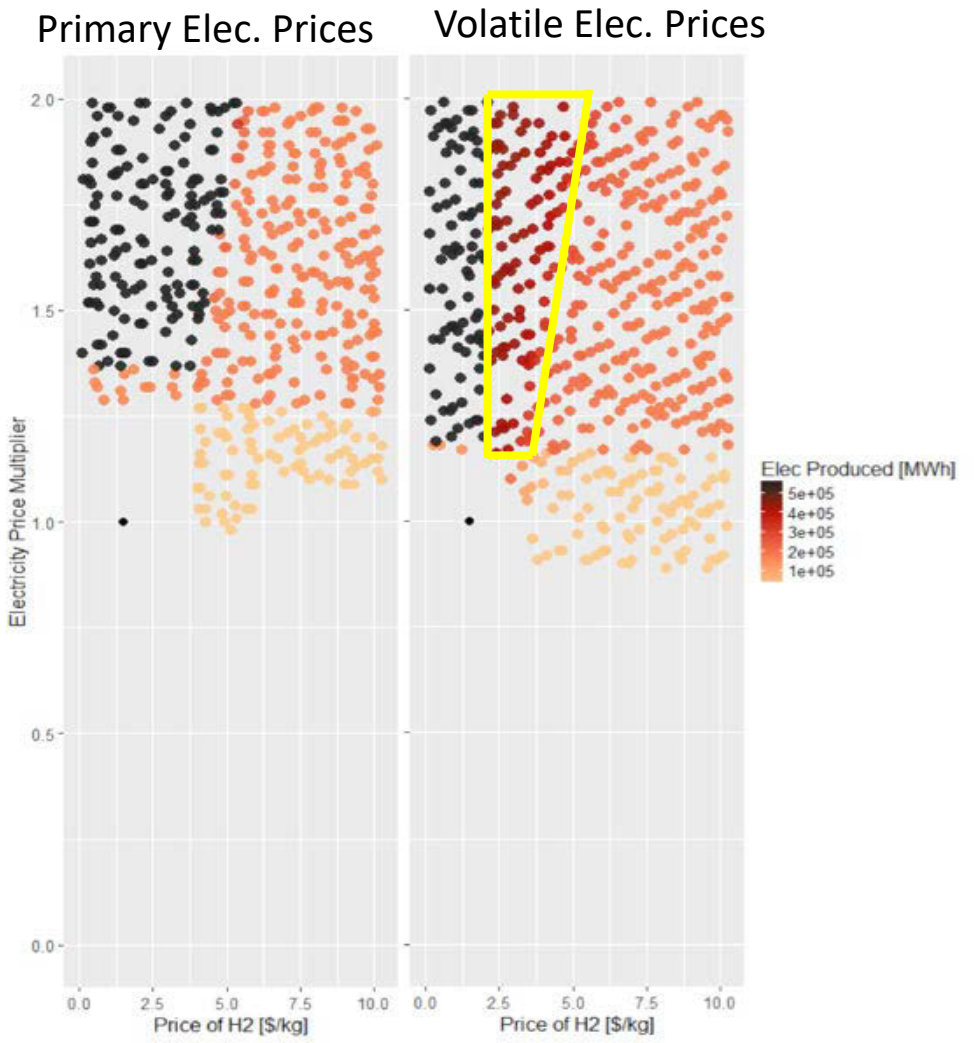
| Price Set | Primary | Arizona | Volatile |
|---|---|---|---|
| Wind generation percentage | 21% | 11% | 8.6% |
| PV generation percentage | 20% | 22% | 37% |
| Hours at $0/MWh annually | 704 | 700 | 2,246 |

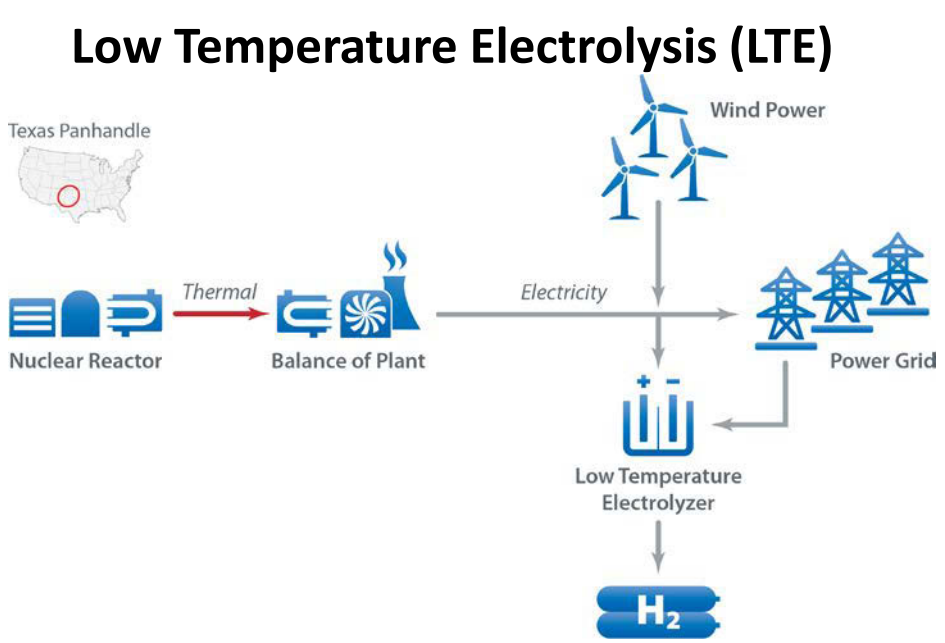
Energy Price Duration Curve for Texas Use Cases




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



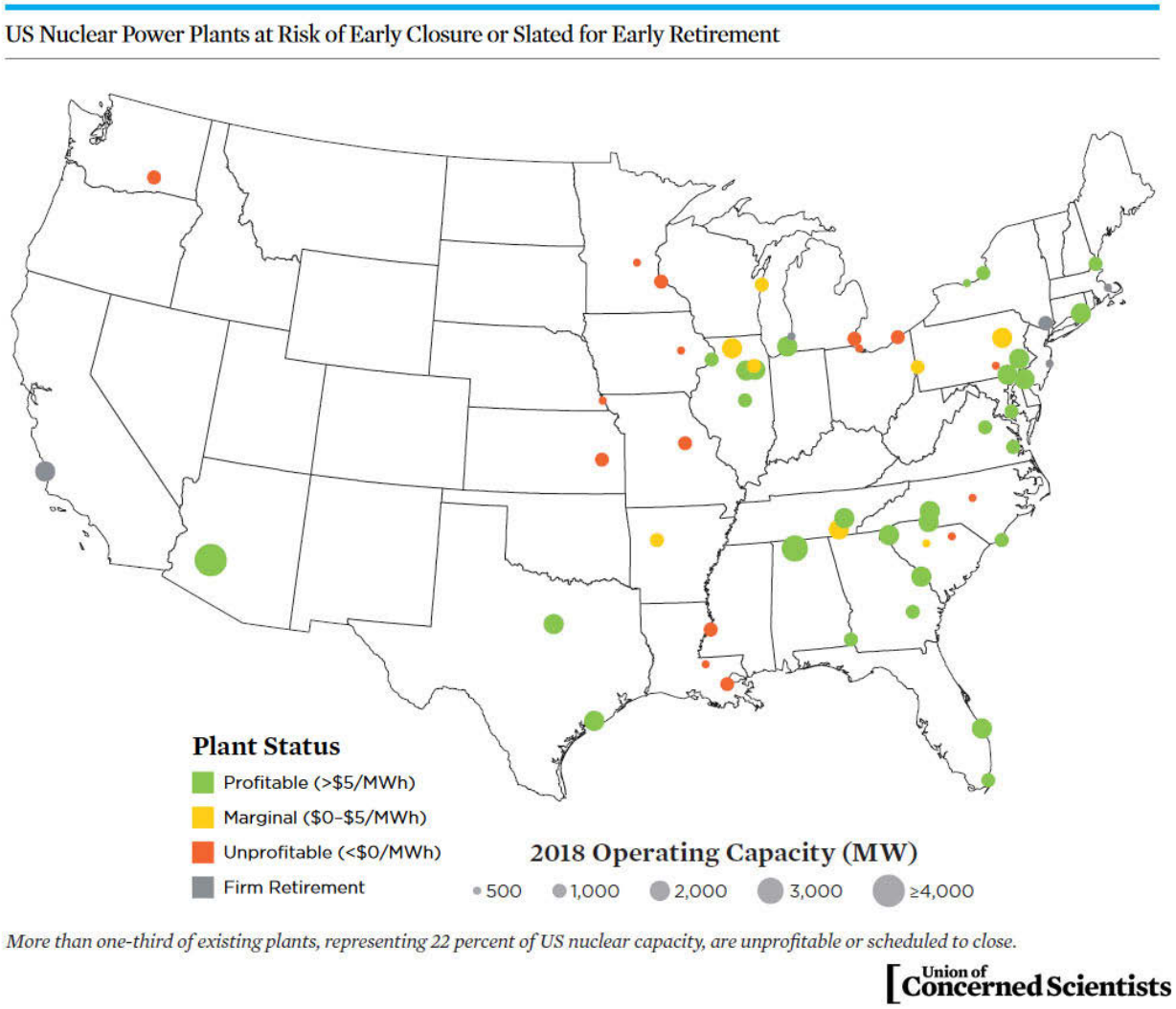

- N-R HES can produce electricity when price is high and industrial product when electricity price is low as shown in the yellow polygon
- High and volatile energy prices necessary to realize the benefits of arbitrage

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.**

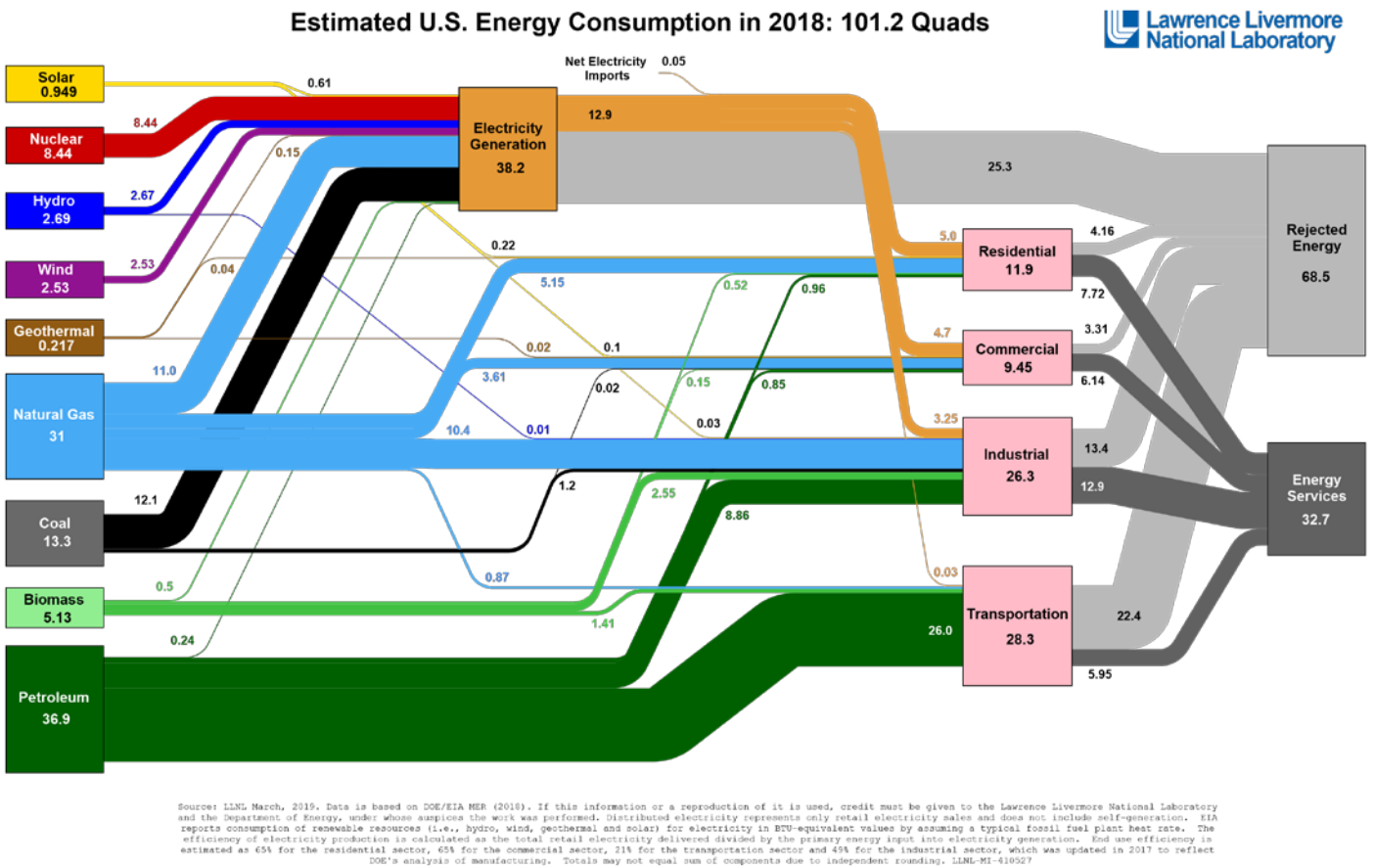
**What is a possible solution?**

**Flexible Generation**

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

# 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 45% 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

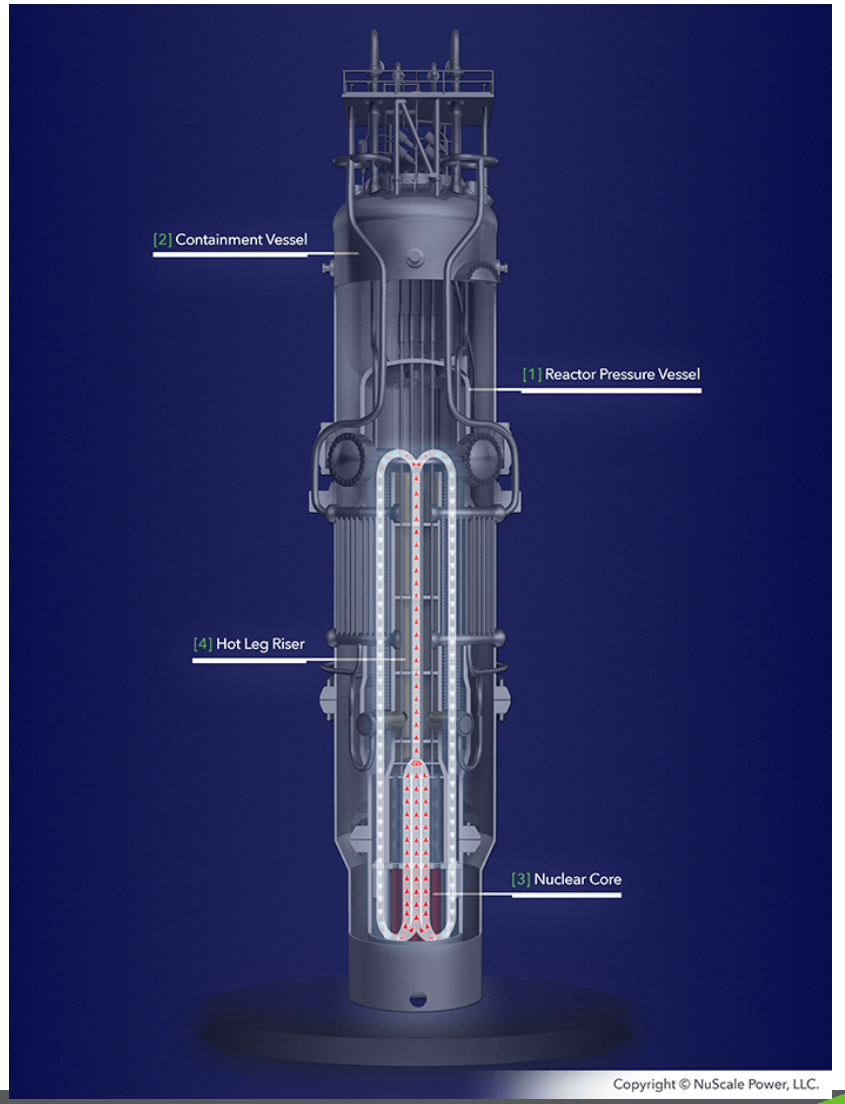
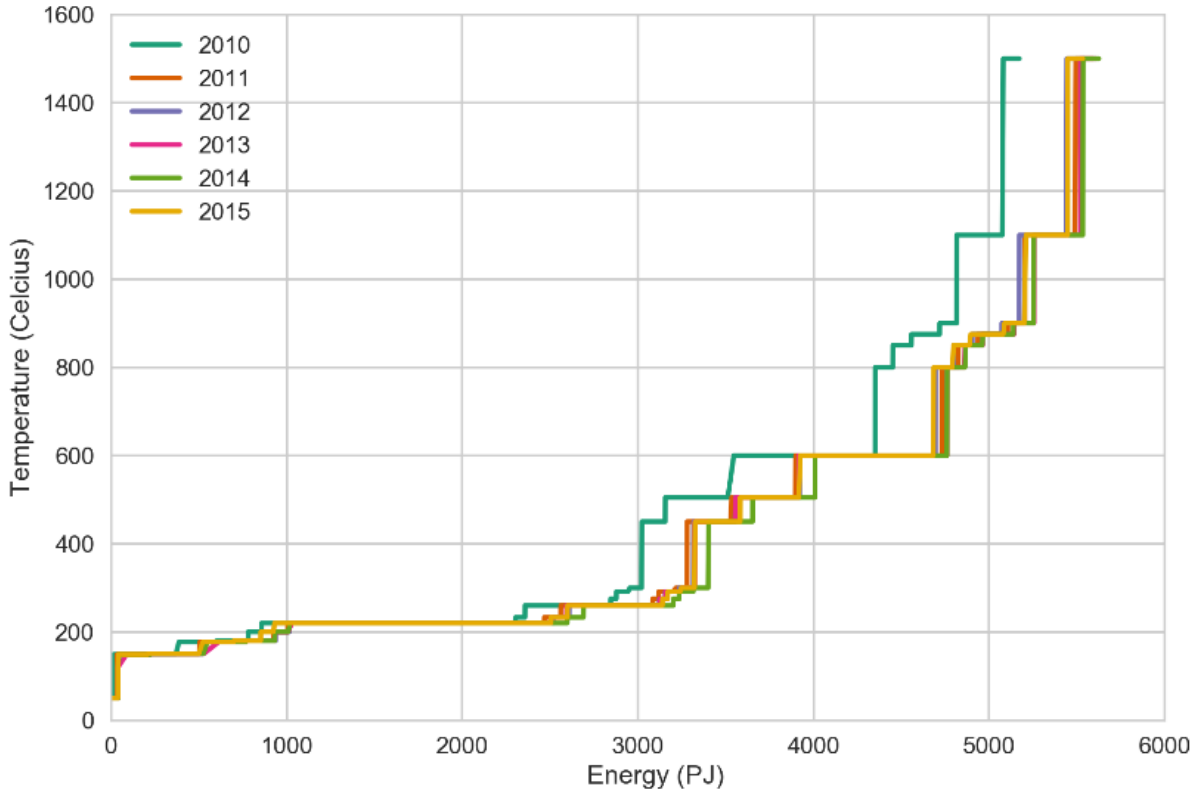



Image Source: https://www.nuscalepower.com/technology/design-innovations (June 19, 2019).

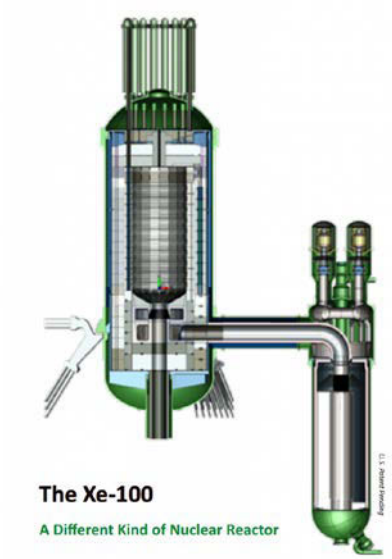
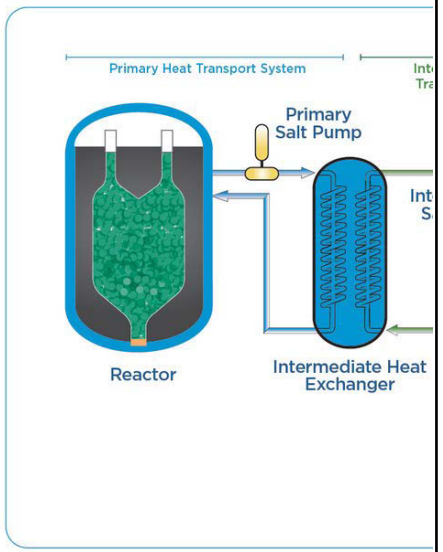
# But Higher Temperatures are Needed for Many Applications




- 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

**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,

# 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)

# 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).

# 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