NREL
Transforming ENERGY

Regional Hybrid Energy Systems Technoeconomic Analysis

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DOE Hydrogen Program
2022 Annual Merit Review and Peer Evaluation Meeting

Project ID: SA175

Project Goal

Evaluate the Potential for Hybridized Nuclear Power Plants to Economically Generate Hydrogen – One Aspect of the H2@Scale Vision

Apply state-of-the art analysis tools and novel methodologies to estimate the value of hybridizing Xcel Energy's nuclear power plants to produce hydrogen

https://www.osti.gov/biblio/1843030/

Overview

Timeline and Budget

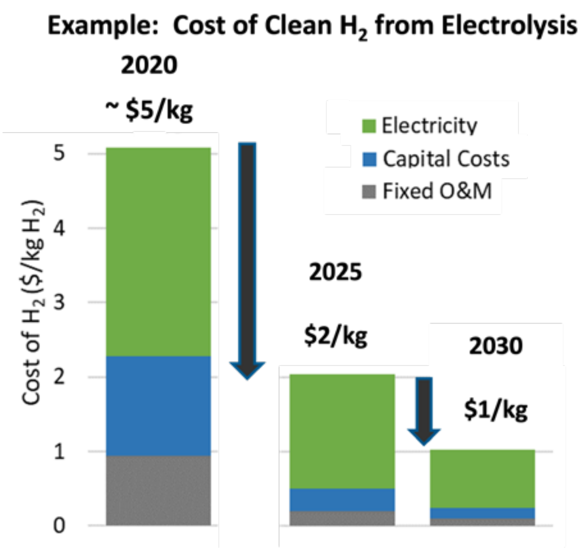
- Project start date: 8/22/19
- FY20 DOE funding (if applicable): $230k to NREL - $500k to ANL - $850k to INL
- FY21 DOE funding: $334k to NREL
- FY22 DOE funding: None
- Total DOE funds received to date*: $564k to NREL - $670 to ANL - $850k to INL

* Since the project started

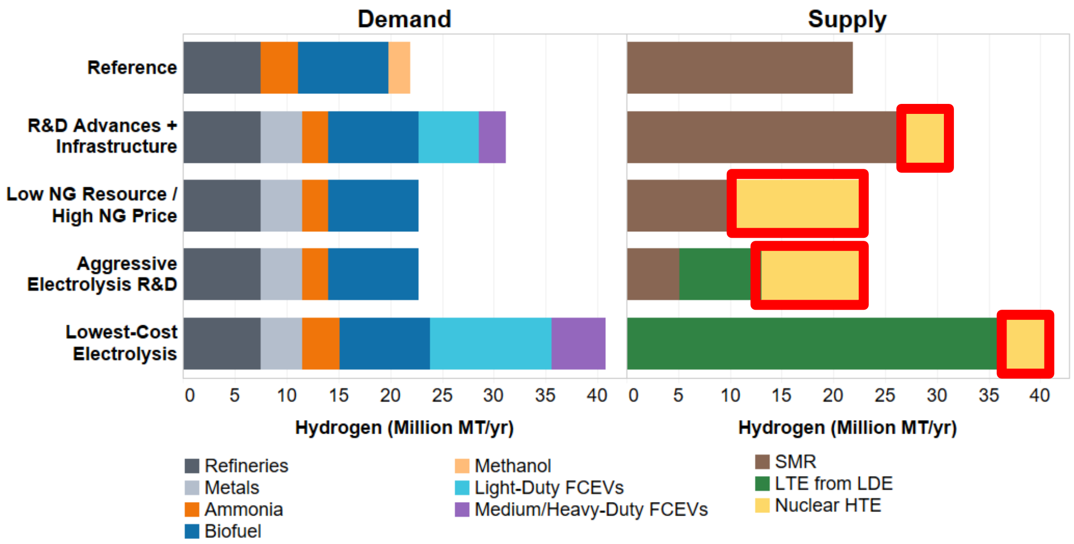
Partners

- Project lead: Todd Knighton (INL)
- Co-PIs: Mark Ruth (NREL) & Amgad Elgowainy (ANL)
- Partner organizations: Xcel Energy (Dan Ludwig); EPRI

Relevance/Potential Impact



Adapted from Sunita Satyapal - https://www.energy.gov/eere/fuelcells/hydrogen-shot-summit



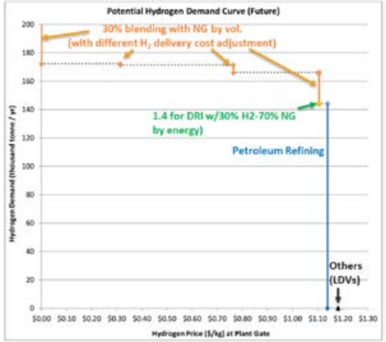
https://www.nrel.gov/docs/fy21osti/77610.pdf

Nuclear-sourced hydrogen is one of the potential opportunities to meet the $1/kg clean hydrogen target (lefthand figure). Analysis of the economic potential of H2@Scale indicates that nuclear energy may provide a large quantity of hydrogen in the future (yellow bars in the righthand figure). This project analyzed the economics of that opportunity for existing nuclear power plants.

Approach

Use Best-in-Class Analysis Tools and Transfer Information Between them to Address Analysis Questions

Hydrogen Market Assessment
(Delivery-adjusted demand curves)
ANL



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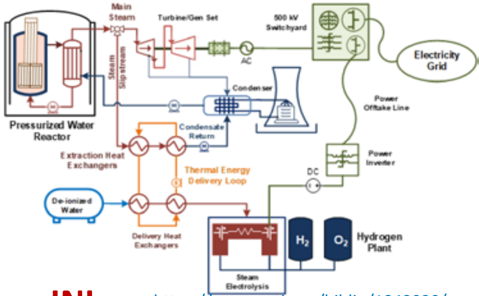
Hydrogen System Cost and Performance Estimates
INL



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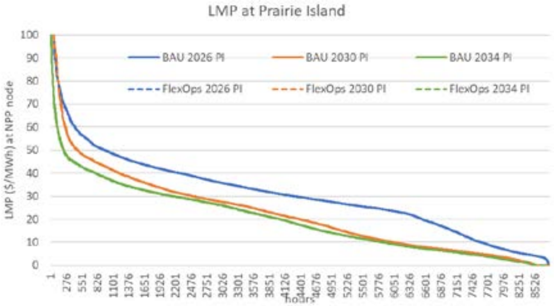
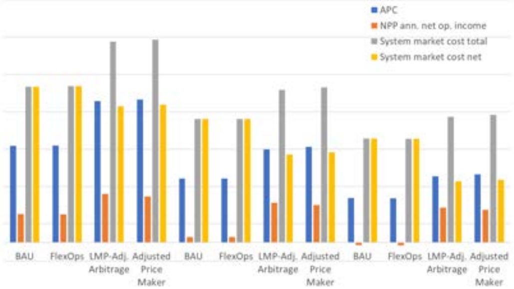
Hydrogen System Configuration Optimization
RAVEN-IES Optimizer
INL

In-depth electricity system modeling
ReEDS, PLEXOS
NREL



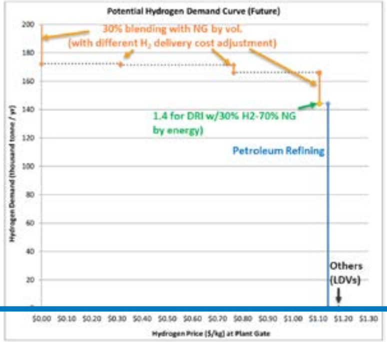


Figures of merit and other metrics
NREL

Approach

Use Best-in-Class Analysis Tools and Transfer Information Between them to Address Analysis Questions

Hydrogen Market Assessment
(Delivery-adjusted demand curves)
ANL



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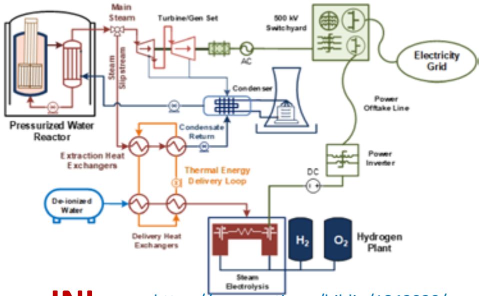
Hydrogen System Cost and Performance Estimates



INL https://www.osti.gov/biblio/1843030/

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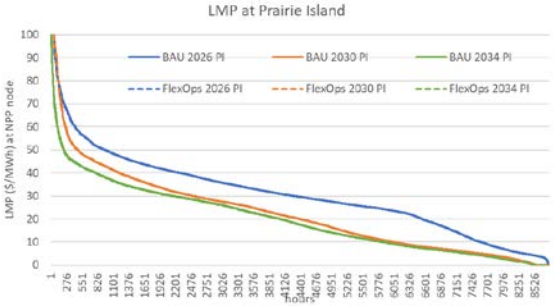
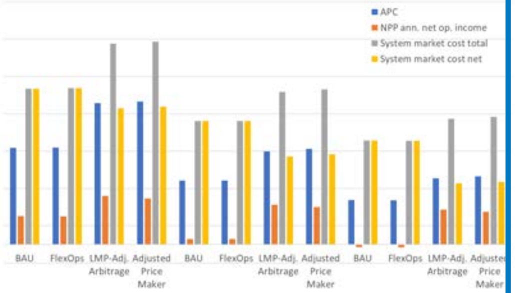


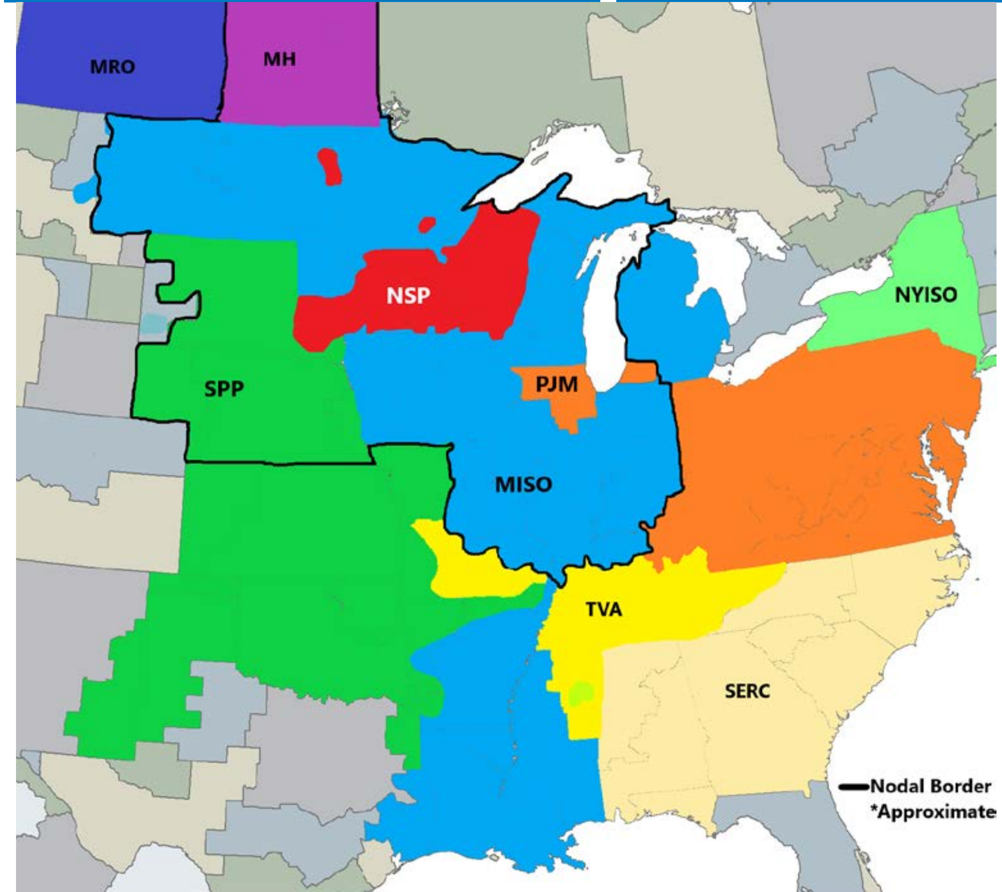


Figures of merit and other metrics
NREL

Last year's AMR discussed the upper two elements. This presentation focuses on interactions between the grid model and hydrogen system optimization and the resulting figures of merit.

Approach

Electricity system modeling with ReEDS and PLEXOS; Hydrogen system modeling with RAVEN



- **Grid generation and transmission buildout**
  - Xcel Energy's Integrated Resource Plan within the Northern States Power territory
  - ReEDS capacity expansion model results for other regions
- **Grid operations**
  - PLEXOS production cost modeling
  - High resolution within the black boundary
  - All other zones: lower resolution (i.e., copperplate inside of zone) and fewer operating constraints
- **Hydrogen system optimization**
  - Electrolyzer size, hydrogen storage size, hourly hydrogen/electricity production, and operating price thresholds
  - Calculate ΔNPV (difference in NPV between each approach and corresponding electricity-only counter factual case)
- **Study years of 2026, 2030, and 2034**

Approach

Hydrogen System Configuration Optimization

Input values:

- Electricity Requirement
- Thermal Requirement
- Electrical Hot Standby
- Thermal Hot Standby
- Cell Degradation Factor
- NPP Thermal Efficiency
- NPP Capacity
- HTSE and storage costs

Hydrogen demand curve

Electricity locational marginal prices (LMPs)

→

RAVEN-IES
Hydrogen System Optimizer

→

ΔNPV

Hydrogen electrolyzer and storage sizes

Power system bidding curves (i.e., “price thresholds”)

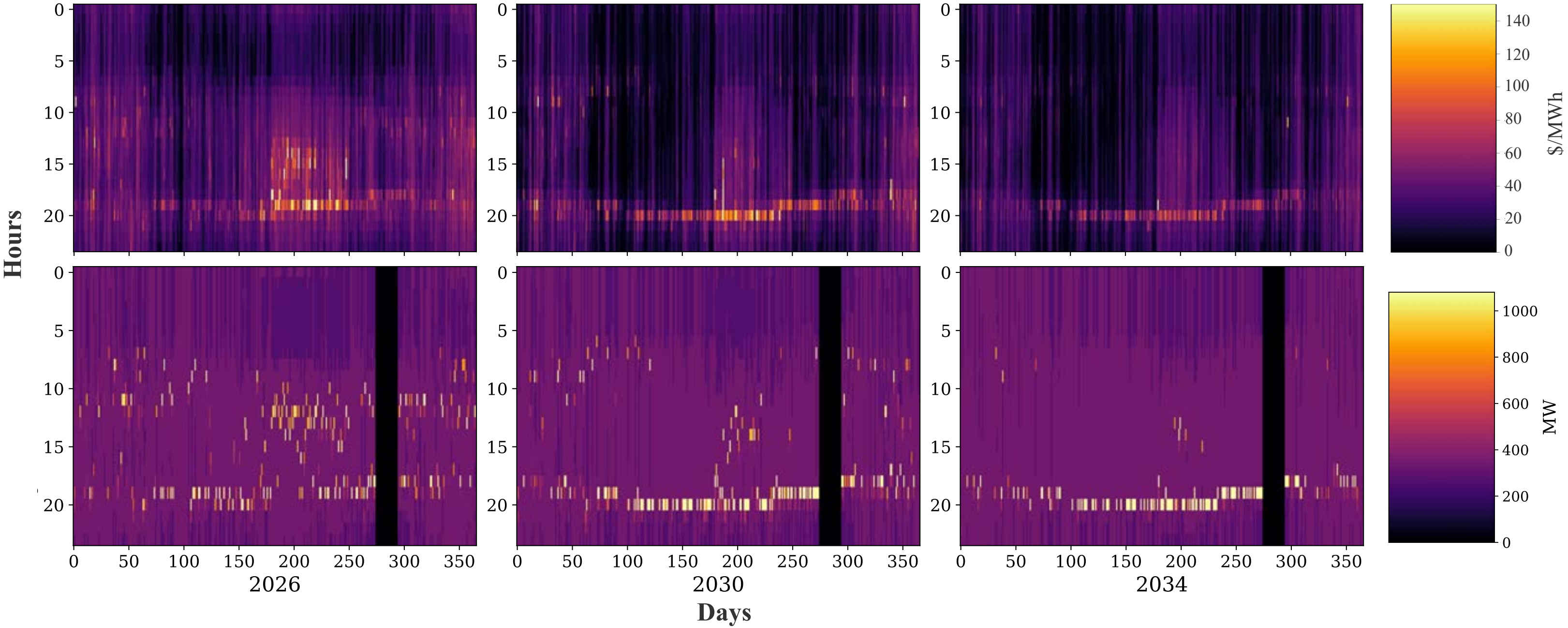
Hybrid NPP electricity and hydrogen hourly profiles

IES = Integrated Energy System

Accomplishments and Progress

Estimated LMPs and corresponding NPP generation for both NPP locations across all years

All results between years are driven by **LMP suppression** due to increased contribution from zero-marginal-cost VRE resources (shown here for Prairie Island for the "Adjusted Price Maker" scenario)



Note: The vertical black-colored bar in the generation plots is an approximation for the refueling outage timing and duration (which corresponds to no electricity to the power system in this example) and, thus, does not reflect specific outage dates.

Approach

Established novel modeling approaches for hybrid NPP-hydrogen systems

- Previous analyses* of hybrid nuclear plants used a **price-taker** approach
- Develop a set of **improved price-taker and price-maker approaches** to addresses the interactions between the electricity system and hydrogen system:
  - LMP feedback effect
  - Hydrogen constraints

	Key Assumption	Pro	Con
Price-Taker	Grid electricity prices are not impacted by electrolyzer integration with an NPP	Simpler/Faster	Ignores impact of nuclear-integrated electrolysis (as represented by changes to hybrid NPP generation profiles) on the rest of the electricity system
Price-Maker	Electricity sold to the grid by the electrolyzer-integrated NPP is determined by pre-set, cost-based bidding curves	More accurate electricity system representation	Ignores real-world physical hydrogen constraints (e.g., constant output requirement, storage limits, and/or impact of intermittent operation on electrolyzer durability)

*e.g., https://www.hydrogen.energy.gov/pdfs/review20/sa175_boardman_2020_p.pdf

Accomplishments and Progress

Established Hybrid NPP Modeling Spectrum

No LMP elasticity but full hydrogen constraints

Full LMP elasticity but no hydrogen constraints

Price Taker
(BAU No Hybrid LMPs with hybrid price taker characterization)

Hybrid response is exclusively optimized by hydrogen constraints; assumes hydrogen output does not impact LMPs

LMP-Adj. Price Taker

Hybrid response is driven by hydrogen constraints; assumes hydrogen output does impact LMP (but not co-optimized)

Adjusted Price Maker

Hybrid response is initially based only on LMPs, then outputs are adjusted to account for hydrogen constraints (but not co-optimized)

Price Maker

Hybrid response is exclusively optimized by LMPs; resulting hydrogen output has no physical limitations

Typical approach: Price Taker

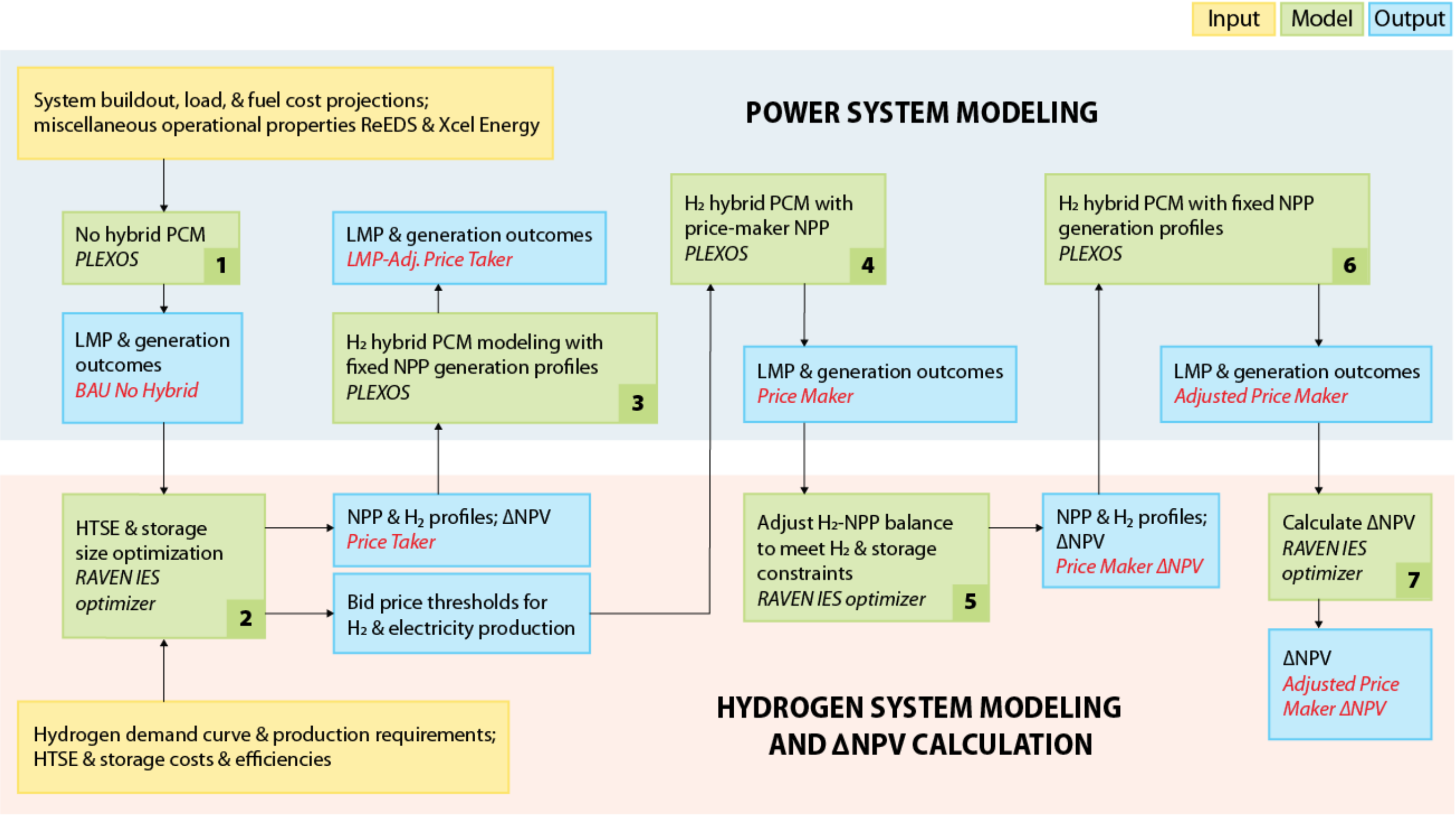
Our improved approaches: LMP-Adj. Price Taker, Adjusted Price Maker

Accomplishments and Progress

Developed iterative method between PLEXOS and RAVEN integrated energy system (IES) optimizer ("RAVEN IES") for a suite of hybrid modeling approaches

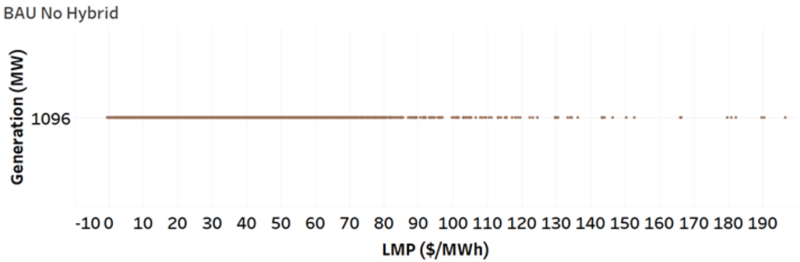
4 core IES modeling approaches

3 ΔNPV calculations

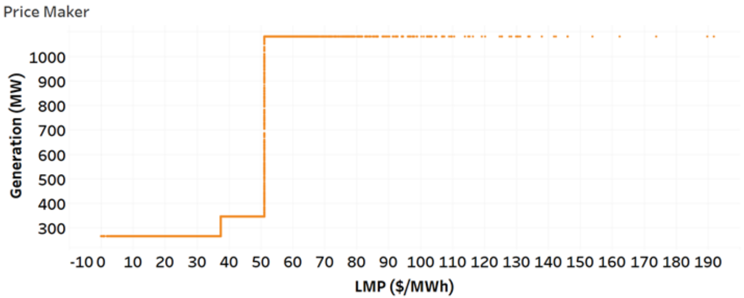


Accomplishments and Progress

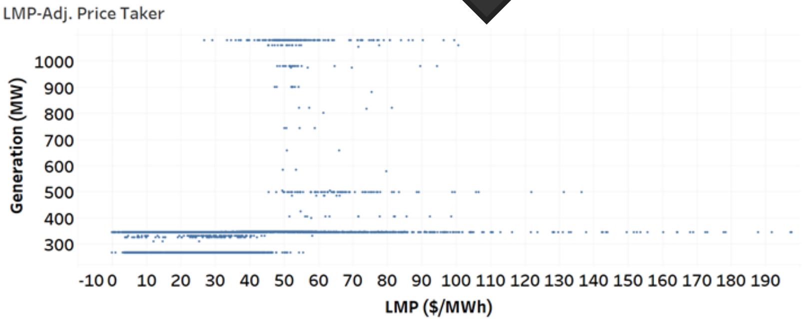
Different modeling approaches yield different hybrid NPP generation (Prairie Island 2026 shown here)



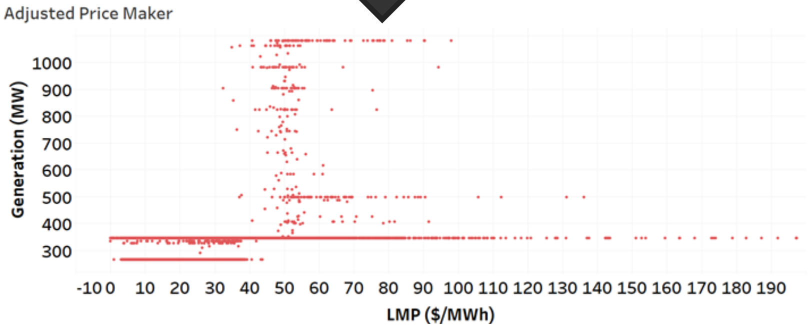
BAU No Hybrid approach always operates the NPP at the maximum electricity output regardless of LMP



Price Maker approach precisely follows its pre-established bidding curve



LMP-Adj. Price Taker approach is very similar to the Adjusted Price Maker approach, suggesting that it may be a reasonable approximation in certain situations, such as when hydrogen constraints dominate the IES outcome



Adjusted Price Maker approach has significantly modified output due to hydrogen output and storage constraints, which cannot be enforced within PLEXOS

Approach

Figures of Merit that Inform Xcel Energy Decisions were Developed within this Project

System operator view →

- **Annual Adjusted Production Cost (APC)**: total variable cost of non-NPP generation in NSP footprint, accounting for sales/purchases with neighboring zones (which may have different locational prices), summed across all hours; no capital costs are included
  – Adapted from Midcontinent Independent System Operator (MISO) metric

NPP owner view →

- **Annual NPP Net Operating Income**: difference between the annual income (energy + H2) and annual operating cost (fuel and fixed operating cost + additional FlexOps cost) of an individual NPP
  – Standard pro forma calculation

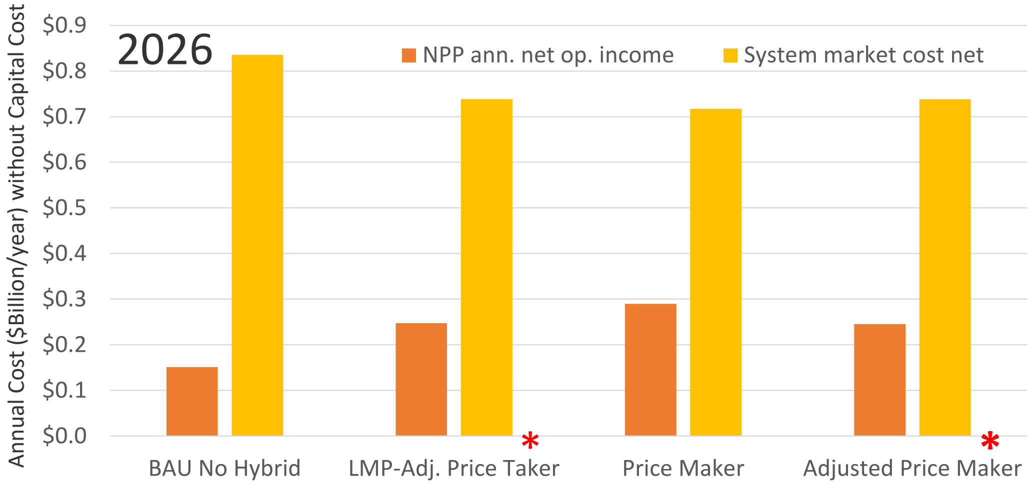
Customer view →

- **System-wide market costs**: APC + Annual NPP Operating Cost. Two methods:
  – **Total** – do not include H2 revenue (i.e., does not benefit customers)
  – **Net** – include H2 revenue (i.e., benefits customers)

Note: all are in $/yr and are based only on PLEXOS modeling runs

Accomplishments and Progress

System-wide market cost results indicated that hybridization provides value to grid and NPP…



Compared to BAU No Hybrid in 2026:

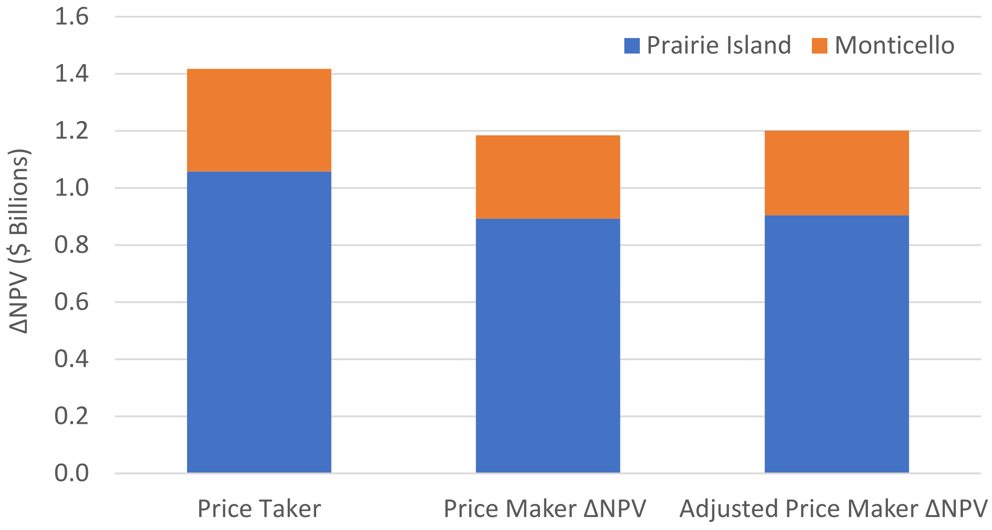
- Systemwide net cost is ~12-14% lower with hybridization (up to 40% lower in 2034)
- NPP annual net operating income is ~62-91% higher with hybridization (over 6x higher in 2030, and changes sign from – to + in 2034)

*Improved methods: capture both LMP feedback and hydrogen constraints

- Hybridizing provides an economic benefit to both the broader NSP system (yellow) and the NPP owner (orange)
  - Decrease in systemwide net cost (total cost minus hydrogen revenues)
  - Increase in NPP annual net operating income (income minus cost)
  - Assumes that the hydrogen revenues benefit the hybrid NPP and broader electricity system/customer

Accomplishments and Progress

…But estimates of the value of hybridization are impacted by the modeling approach used



The price taker approach over-estimates the value of hybridization

- ΔNPV is an indicator of the profitability of hybridization within a single modeling approach (relative to a counterfactual non-hybridization case). It involves both capital and operating costs.

- The Price Taker's comparatively large ΔNPV value results from the use of smaller, non-updated LMPs.
  - Presents an overly optimistic view of the value of hybridization because the LMP feedback effects are not considered (i.e., it does not capture LMPs' elasticity).

Accomplishments and Progress:
Response to Previous Year Reviewers' Comments

- "The project could demonstrate greater use of risk identification and mitigation. For example, the team could determine what would happen if HTE is not available when needed, if "guesses" about the demand curve (as stated in the oral presentation) turn out not to be correct, or if the dynamic functioning of the plant and electrolyzer do not operate as planned."
  - **Response**: This project is a preliminary analysis. Risk identification, quantification, and mitigation would require additional funding to increase the scope and timescale.
- "Expanding the analysis to additional cases and technologies would help define which technologies might best fit different energy scenarios while achieving different price targets."
  - **Response**: We agree that such sensitivities would provide additional value, but additional funding would be required to support that work.
- "The project could benefit from input from hydrogen end users such as natural gas-fired power plants. Also, next year's presentation could include a figure on the intersection of supply and demand curves."
  - **Response**: Hydrogen end users (including gas-fired power plants with a blended hydrogen-gas source) are included in the updated demand curves. We used an optimization approach to match supply, demand, and pricing thus a supply-demand figure is not available.
- "New tools are described well, but the linkage of these efforts to addressing the $2/kg barrier is not as clear"
  - **Response**: A key component of the $2/kg target is the electricity price. This effort focuses on accurate estimations and quantifications of that price.

https://www.hydrogen.energy.gov/pdfs/review21/2021-amr-08-systems-analysis.pdf

Collaboration and Coordination

Xcel Energy (Cost Share)

- Project Objectives & Direction
- Grid & nuclear power plant data and performance

Hydrogen & Fuel Cell Technologies Office Funding		Nuclear Energy Office Funding	
NREL	**ANL**	**INL**	**EPRI**
• Methodology Development • Grid Modeling • Figures of Merit • Initial price-taker assessment of hybrid system	• Identification of hydrogen demands • Demand curves	• HTSE cost and performance • Optimization of hybrid system cost and operations	• Nuclear power industry connections • Grid modeling review

Remaining Challenges and Barriers and Proposed Future Work

Project is complete and further efforts are not currently planned.

Priority challenges and barriers that could be addressed by future work

Challenges & Barriers	Potential Future Work
Validity of the current assumption is that hydrogen will be purchased during NPP refueling periods is unknown.	Review strategy to provide hydrogen to customers during NPP refueling periods.
Hydrogen storage for exclusive use by the hybrid system is expensive.	Evaluate the potential for networked hydrogen storage that the system can leverage instead of requiring its own storage.
Iterative approaches for the two optimizations are time-consuming and may be inaccurate.	Develop tools that make co-optimization of grid operations and the hybrid energy system tractable without oversimplifying.
Impacts of operating risks are unknown.	Identify, evaluate, and develop mitigation strategies for potential operational issues.
Analysis assumes hydrogen market is 100% available when the hybrid system is constructed.	Develop a buildout plan that addresses hydrogen market growth and considers multiple electrolyzers built at different times.
The analysis was performed for a single location and expected grid. The results and conclusions may not be generally applicable.	Expand the analysis to include additional technologies and grid portfolios to estimate the robustness of the results.

Summary

- **Hybridization is of value**
  - Under our assumptions and test system, hybridization of NPPs with hydrogen production can benefit both the hybrid NPP and broader system, provided hydrogen revenues are shared appropriately between the hybrid NPP and power system/customer

- **The methodology for modeling hybrid NPP-hydrogen systems can have highly nuanced impacts on results**
  - Optimal operations are based on power system LMPs, the cost to produce and store/transport hydrogen, and the opportunity cost for hydrogen as determined by the broader hydrogen market
  - Modeling these systems without considering each component can lead to inaccurate results
    - The typical price-taker approach overestimates the value of hybridization

- **The evolution of the power system impacts the economic outlook for hybrid resources**

- **Future work could explore the robustness of results against different hydrogen production and storage cost parameters**

Thank You

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NREL/PR-6A40-82547

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Technical Backup and Additional Information

Technology Transfer Activities

- This project is directly informing demonstration projects for hybrid integration of hydrogen production at nuclear power plants at Xcel Energy and other interested utilities.
- Potential follow-on activities at Xcel Energy and other utilities will use the information from this project to inform investment decisions.

Special Recognitions and Awards

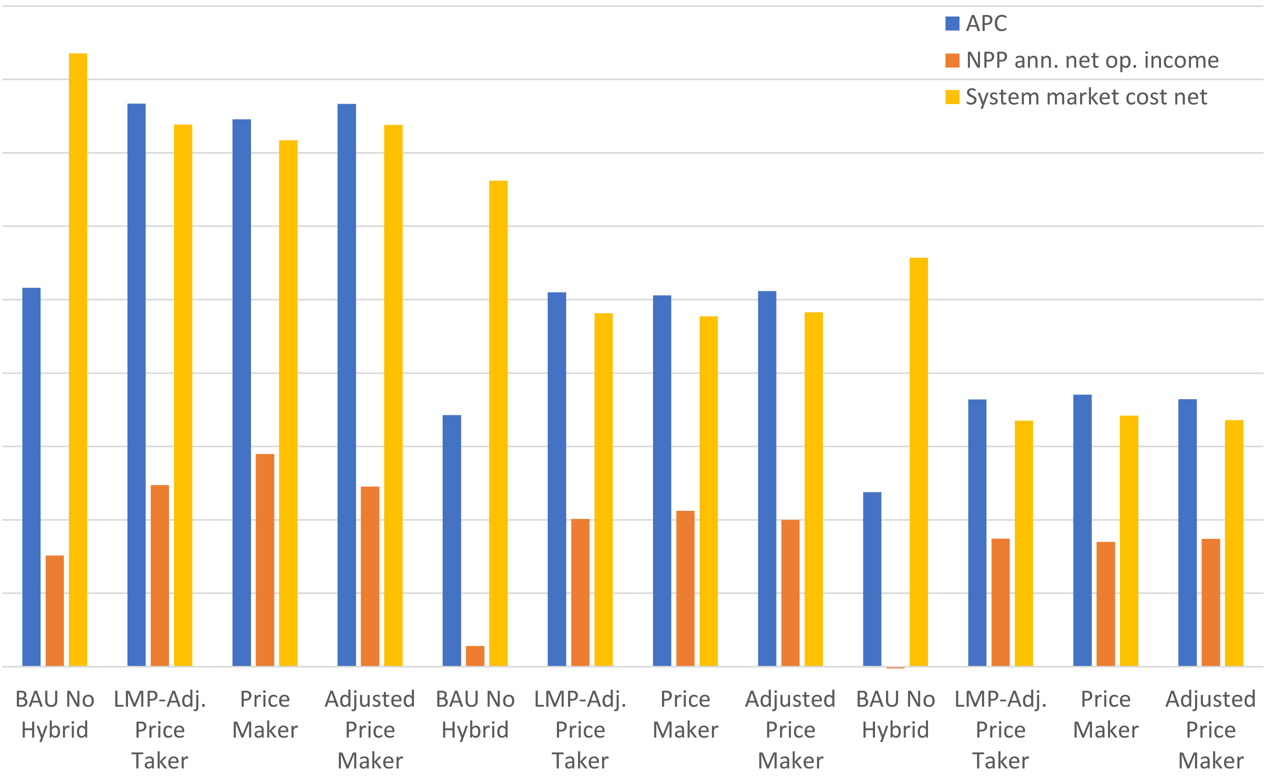
- This work is part of and building off work that was awarded a 2019 U.S. Department of Energy Secretary’s Honor Award
- This project partially supported work that was recognized in a 2020 Energy Systems Integration Group (ESIG) Excellence Award “For contributions to market design for a renewable energy future” awarded to Bethany Frew and others.

Publications and Presentations

- Frew, B., D. Levie, J. Richards, J. Desai, and M. Ruth. Submitted. Modeling multi-output hybrid energy systems as price-maker resources. *Applied Energy*.
- Frew, B., M. Ruth, D. Levie, and J. Desai. Forthcoming. Estimating Grid Benefits of Hybridized Nuclear Power Plants for Xcel Energy: Final Report. Internal-only NREL technical report NREL/MP-6A20-78447.
- Richards J, Knighton LT, Wendt D, Elgowainy A, Ludwig D, Rabiti C, et al. (Submitted). Development of Economic Dispatch Model for Evaluating Nuclear-Hydrogen Integrated Energy System Profitability. *Applied Energy*.
- Knighton, Lane T, Wendt, Daniel S, Richards, James D, Rabiti, Cristian, Abou Jaoude, Abdalla, Westover, Tyler L, Vedros, Kurt G, Bates, Samuel, Elgowainy, Amgad, Bafana, Adarsh, Boardman, Richard D, Reddi, Krishna, Zang, Guiyan, Ruth, Mark, Frew, Bethany, Levie, Daniel, Jadun, Paige, Desai, Jal, Bernhoft, Sherry, Westlake, Brittany, McCollum, David, Ludwig, Daniel, Strasser, Molly, and Ramler, Bryan. 2021. Techno-Economic Analysis of Product Diversification Options for Sustainability of the Monticello and Prairie Island Nuclear Power Plants. INL/EXT-21-62563-Rev001. doi:10.2172/1843030.

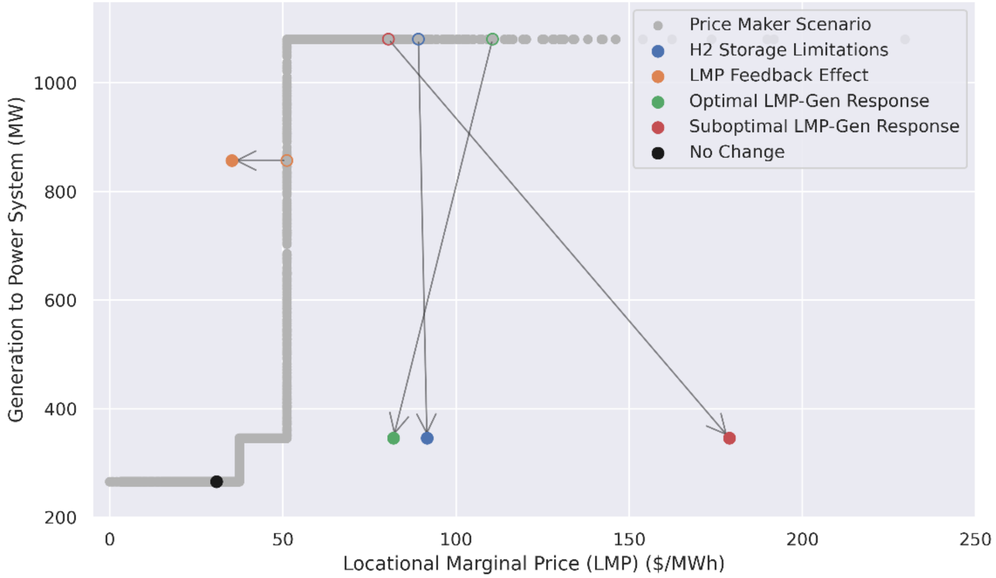
Additional results

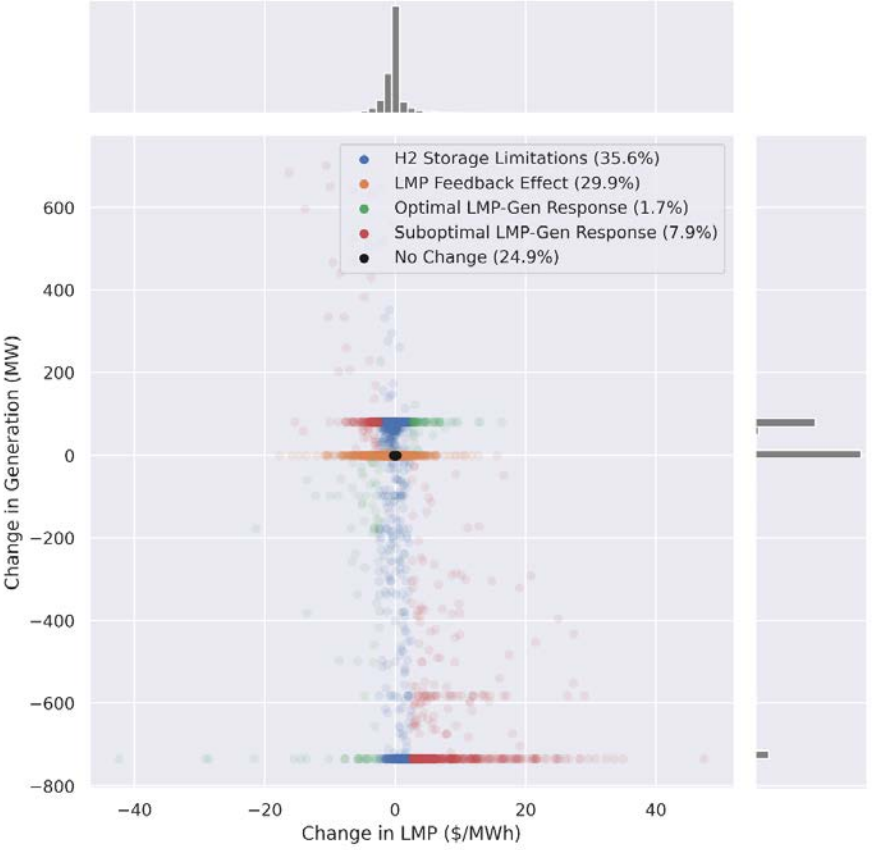
All Figures of Merit



- **All metrics** decrease as between 2026 and 2034 due to an increase in lower marginal cost resources (e.g., wind and solar PV)
  - NPP loses money in 2034 for BAU due to a reduction in energy prices
- **Hybridizing** provides an economic benefit to both the broader NSP system (yellow) and the NPP owner (orange) compared to BAU

How much do hydrogen constraints matter?





Compare 3 vs 4:

Adjusted Price Maker vs. Price Maker approach, the latter of which perfectly follows the "price threshold" bidding curve

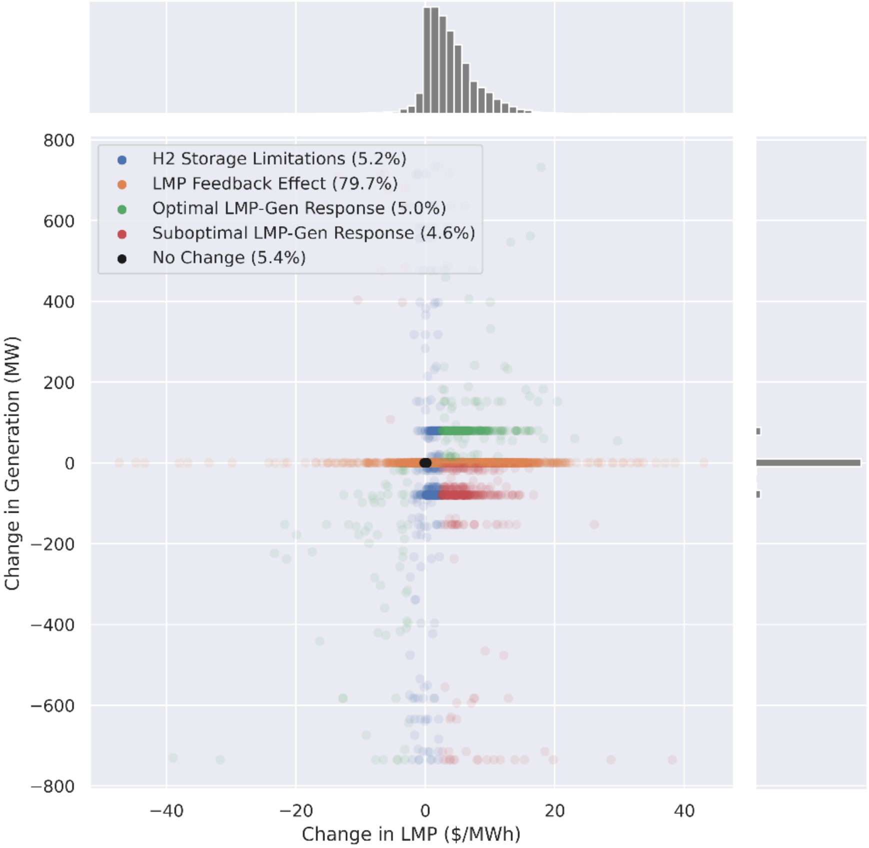
Hydrogen constraints impact both LMP (net increase) and generation (net decrease), with opposite impact in later years due to overall LMP reduction

How much does improved price-maker differ from traditional price-taker?

Compare 1 vs 3:

Traditional Price Taker vs. Adjusted Price Maker approach

Very little impact on generation, but significant impact on LMPs → Traditional Price Taker approach fails to capture this LMP feedback



What is impact of including LMP feedback AND hydrogen constraints?

Compare 2 vs 3:

LMP-Adj. Price Taker vs. Adjusted Price Maker approach

Results are very similar → both approaches are suitable in this case, but may differ in cases where hydrogen constraints do not drive results