Impacts of High Variable Renewable Energy Futures on Electric-Sector Decision Making: Demand-Side Effects

Implications for Energy Efficiency Valuation, Retail Rate Design, and Opportunities for Large Energy Customers

Joachim Seel, Andrew Mills, Cody Warner, Bentham Paulos, Ryan Wiser

Lawrence Berkeley National Laboratory

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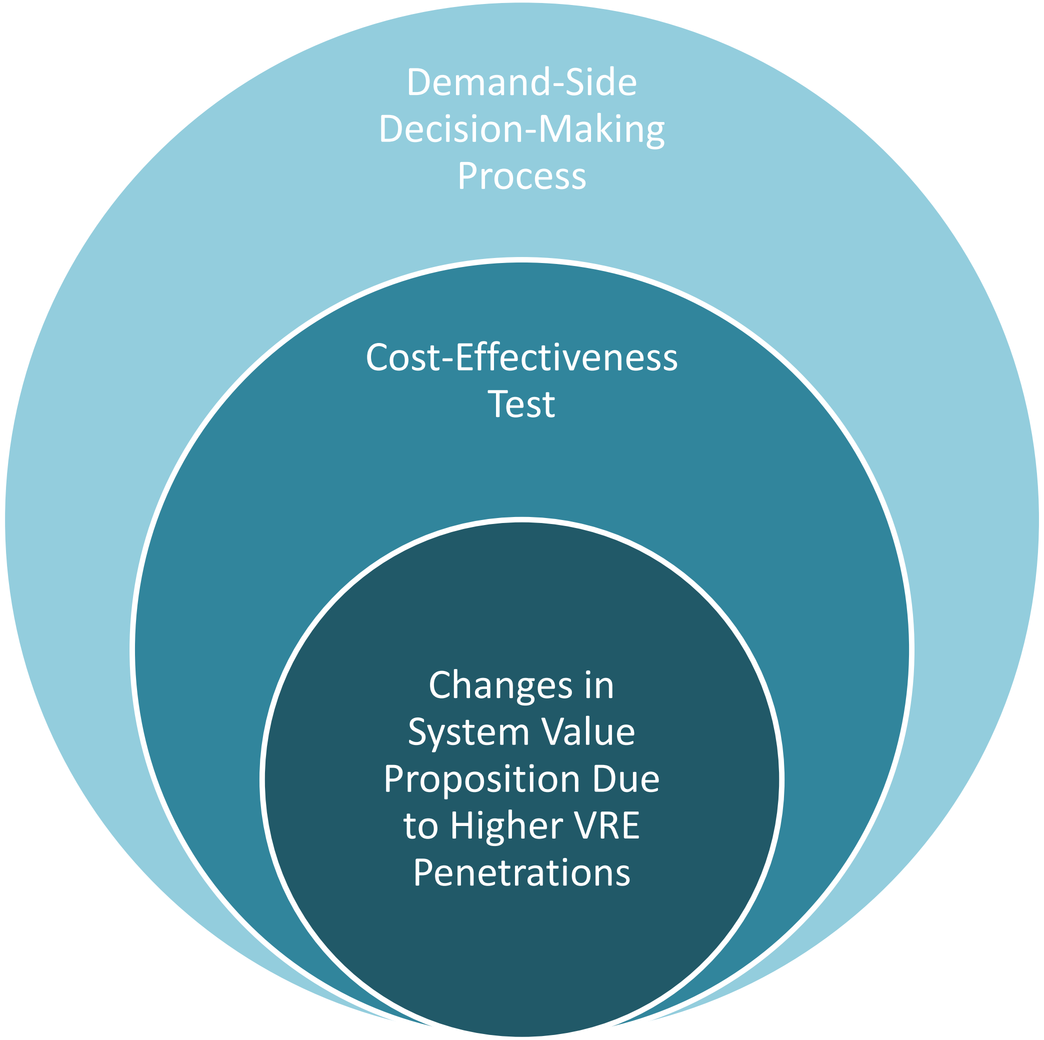
Project Overview

- Many long-lasting decisions in the electricity sector are made based on historical observations or a business-as-usual future. If the variable renewable energy (VRE) share increases, however, **fundamental characteristics of the power system would change.**
- The objective of this research is to inform decision-makers about **impact of high VRE penetrations on the cost-effectiveness of long-lasting electric sector decisions.**
- We utilize wholesale market simulation tools to estimate **wholesale prices: Energy, Capacity, AS** (https://emp.lbl.gov/publications/impacts-high-variable-renewable).
- We subsequently analyze implications of wholesale price changes on demand-side resources. We highlight how program design and investment decisions would be meaningfully different in a high VRE environment.
- Our assessed examples include energy efficiency valuation, retail rate design, and large electricity consumers and emerging applications at a scoping level.

Relevance of System Value Changes for Demand-Side Decisions

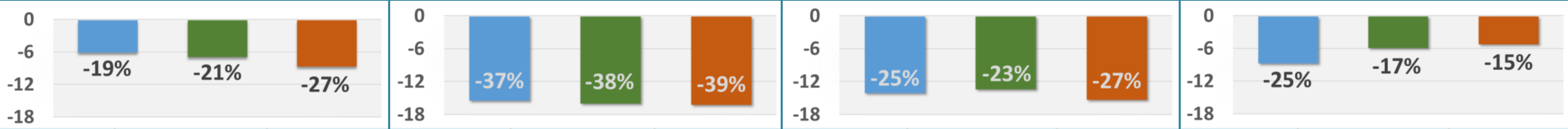


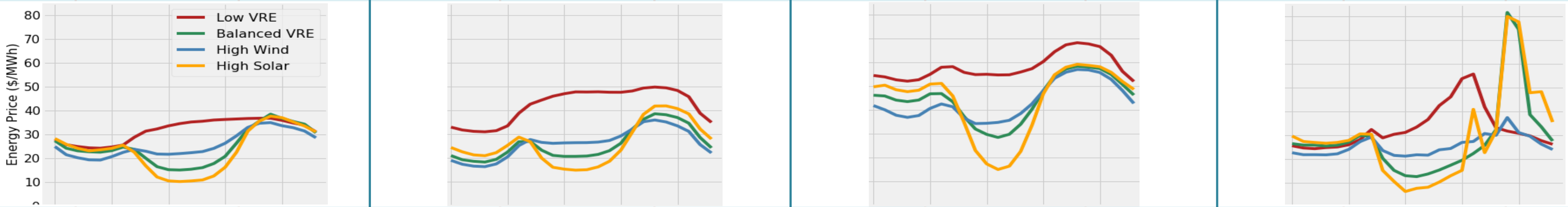
- Decisions about demand-side programs or investments are complex and incorporate many considerations.
- Cost-effectiveness tests inform economic efficiency evaluations and are often part of the decision-making process.
- Changes in power system dynamics can affect the value proposition of various demand-side assets and their cost-effectiveness.
  - We leverage previously modeled wholesale electricity prices as proxy for the changing **marginal system value**.

Wholesale Price Effects of 40%-50% Wind & Solar

(Wind: 30% wind & 10+% solar | Balanced: 20% wind & 20% solar | Solar: 30% solar & 10+% wind)

Impacts in 2030 relative to baseline with 2016 wind & solar shares	**Southwest Power Pool** 2016: 18% wind & 0% solar			**NYISO (New York)** 2016: 3% wind & 1% solar			**CAISO (California)** 2016: 7% wind & 14% solar			**ERCOT (Texas)** 2016: 16% wind & 1% solar		
	Wind	Balanced	Solar	Wind	Balanced	Solar	Wind	Balanced	Solar	Wind	Balanced	Solar
Lower Average Prices [$/MWh]	-19%	-21%	-27%	-37%	-38%	-39%	-25%	-23%	-27%	-25%	-17%	-15%
More Hours <$5/MWh In baseline: 0% of all hours	6%	8%	13%	2%	7%	11%	6%	7%	11%	6%	11%	19%
Changes in Diurnal Price Profile red baseline shows 2016 wind & solar shares												
More Price Variability	1.8x	2.1x	2.5x	2.1x	2.3x	2.5x	3.0x	2.9x	3.4x	1x	4.7x	6.6x
Higher AS Prices Regulation Down	5x	6x	9x	2x	2x	3x	3x	3x	3x	2x	3x	4x
Change in Timing of Top Net-Load Hours	Shift from 4pm to 7pm			Shift from 3pm to 5-7pm			No further shift 7pm			Shift from 3pm to 6-8pm		



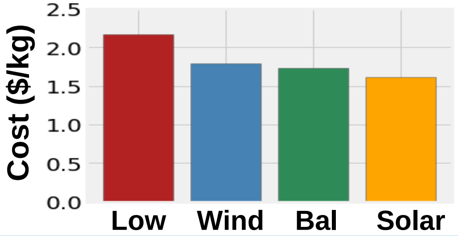


Decision Changes with 40%-50% Wind & Solar

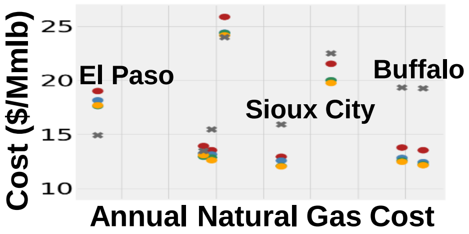
(Wind: 30% wind & 10+% solar | Balanced: 20% wind & 20% solar | Solar: 30% solar & 10+% wind)

Impacts in 2030 relative to 2016		Southwest Power Pool 2016: 18% wind & 0% solar				NYISO (New York) 2016: 3% wind & 1% solar				CAISO (California) 2016: 7% wind & 14% solar				ERCOT (Texas) 2016: 16% wind & 1% solar			
		Low	Wind	Bal'd	Solar	Low	Wind	Bal'd	Solar	Low	Wind	Bal'd	Solar	Low	Wind	Bal'd	Solar
Relative value rankings of energy savings measures	Res HVAC	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
	Res Light	9	5	3	2	9	6	3	2	3	2	2	2	9	6	2	2
	Com HVAC	2	4	5	6	2	3	4	6	4	4	4	5	3	3	7	7
	Com Light	7	9	9	9	5	7	9	9	8	8	8	9	5	8	9	9

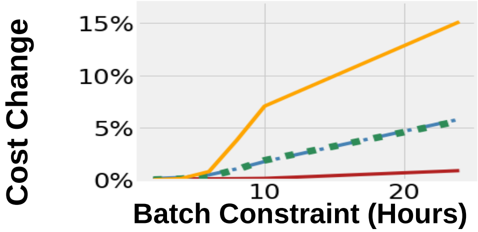
Declines in levelized per-unit costs of electricity-intensive products



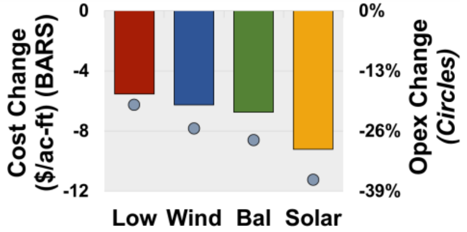
Declining production costs (ex: H_2)



Greater value for fuel flexibility (ex: district heating)



High costs for inflexible processes (ex: industry)



Greater value for product storage (ex: desalination)

Economic efficiency gains vs. flat rate		SPP Low	SPP Wind	SPP Bal'd	SPP Solar	NYISO Low	NYISO Wind	NYISO Bal'd	NYISO Solar	CAISO Low	CAISO Wind	CAISO Bal'd	CAISO Solar	ERCOT Low	ERCOT Wind	ERCOT Bal'd	ERCOT Solar
	TOU2	57%	61%	64%	70%	50%	64%	66%	70%	76%	61%	68%	74%	61%	64%	81%	76%
	TOU3	60%	67%	72%	77%	47%	67%	71%	72%	77%	65%	70%	76%	63%	66%	84%	80%
	CPP + TOU3	99%	99%	99%	99%	95%	98%	97%	97%	99%	95%	96%	95%	93%	97%	93%	93%

Value Streams Considered in Our Analysis

- Focus on broad directional changes that policy makers should consider.
  - Not a full replication of total cost-effectiveness tests.
- Limitations of our analysis:
  - Not a comprehensive analysis of all value streams.
  - Marginal value assessment only.
    - no assessment of market depth.
  - Limited scenario analysis.
  - Only modeled single year.

Value Streams Considered in Our Analysis

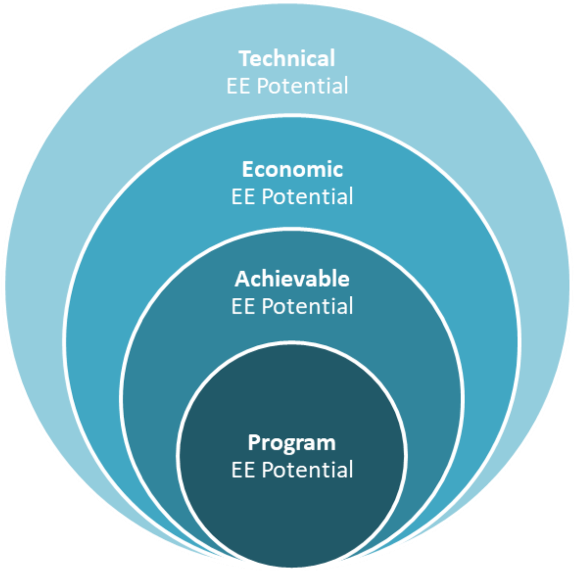
Included
- Energy
- Generation capacity (over top 100 net-load h)
- Internalized environmental costs

Excluded
- Transmission system
- Distribution system and locational value
- Line losses
- Reserve requirements
- Fuel price risks
- Demand change-induced price effects
- Externalized environmental costs
- Broader economic development impacts

Energy Efficiency Valuation

VRE Impacts on Energy Efficiency– Overview of Issue

- Central task for utility administrator is the selection of suitable combinations of energy efficiency (EE) measures that:
  - decrease overall energy consumption.
  - curb demand growth.
  - reduce overall electric system needs and costs.
  - meet explicit energy efficiency resource standards.
  - reduce customer bills.
- **With changing energy supply options and changing peak and off-peak periods the composition of the best EE portfolio will likely change.**

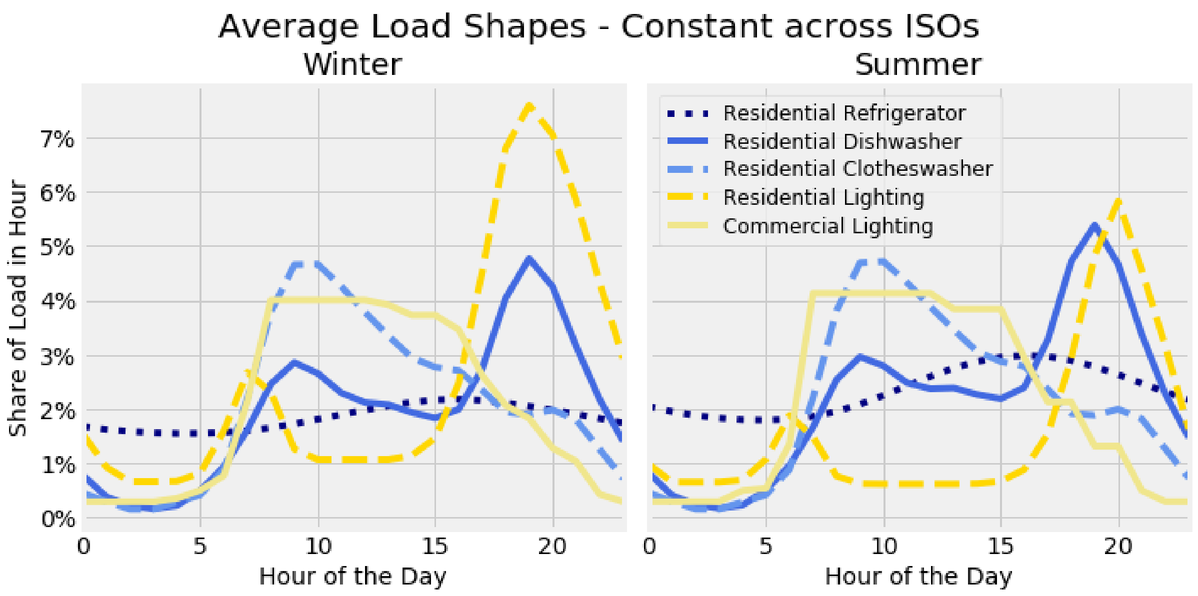


Analytical Approach and Load Profiles (1)

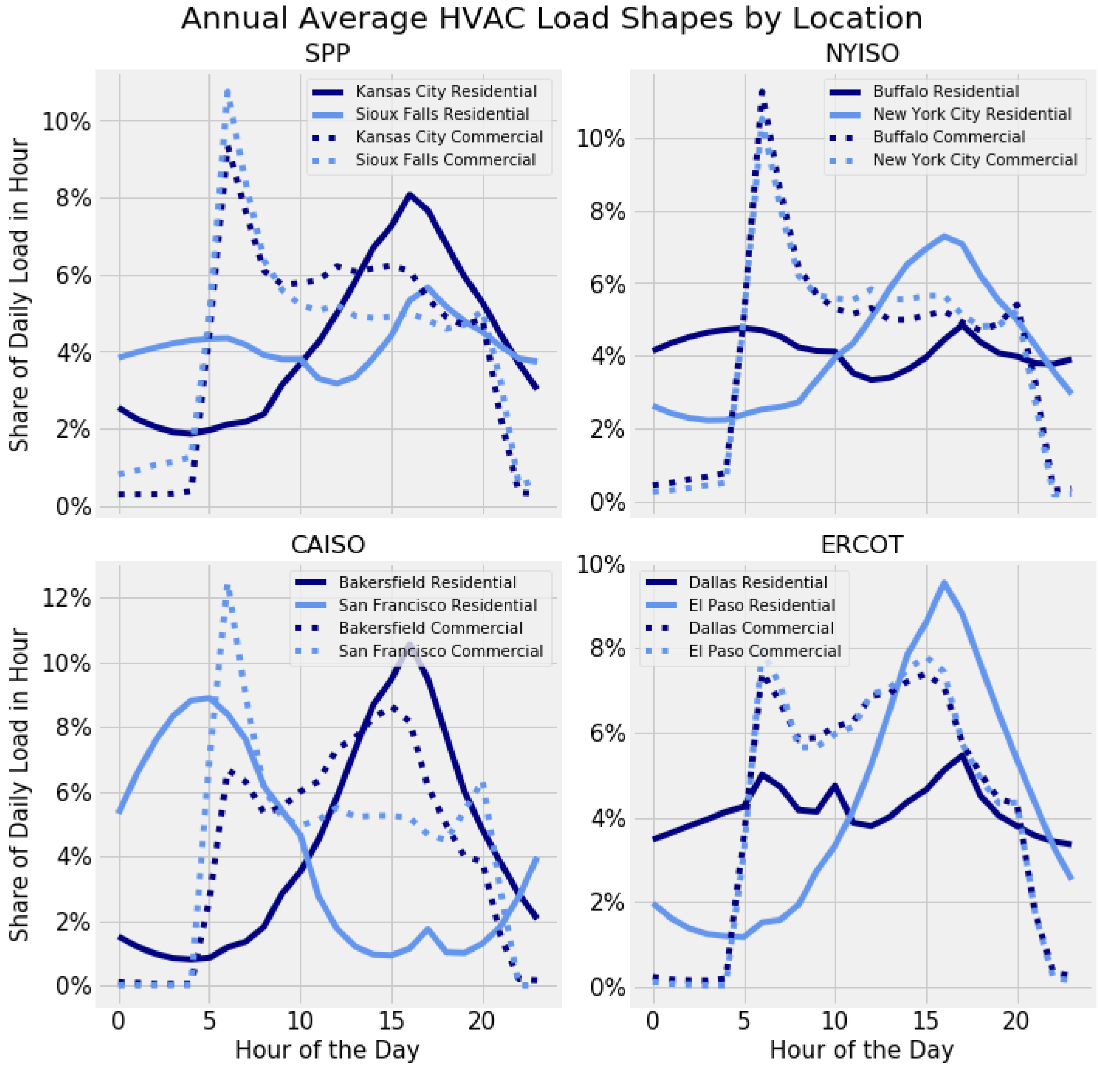
Method: We approximate EE value as the product of time-varying wholesale electricity prices and EE profiles.

- Limited data available for empirical EE savings shapes that have high time and geographic resolution. Instead of saving shapes we use 8760h load shapes whose profile is assumed to be congruent with EE savings (i.e. no upgrade induced profile changes/inclusion of demand response).
- Focus is on directional change in time-dependent value: We normalize appliance-specific EE savings to 1MWh per year to allow for better comparability – effectively disregarding differences in the absolute magnitude of energy consumption.
- Due to data constraints we limit our analysis of energy and capacity value changes: as we do not assess required investment costs these should not be equated with total net-benefit changes.

- Location-independent load profiles:
  - Residential and commercial lighting shapes based on "Build America Simulations" (annual energy consumption varies by location but not shape).
  - Appliance load shapes based on California Database for Energy Efficient Resources (2011) for PG&E territory.

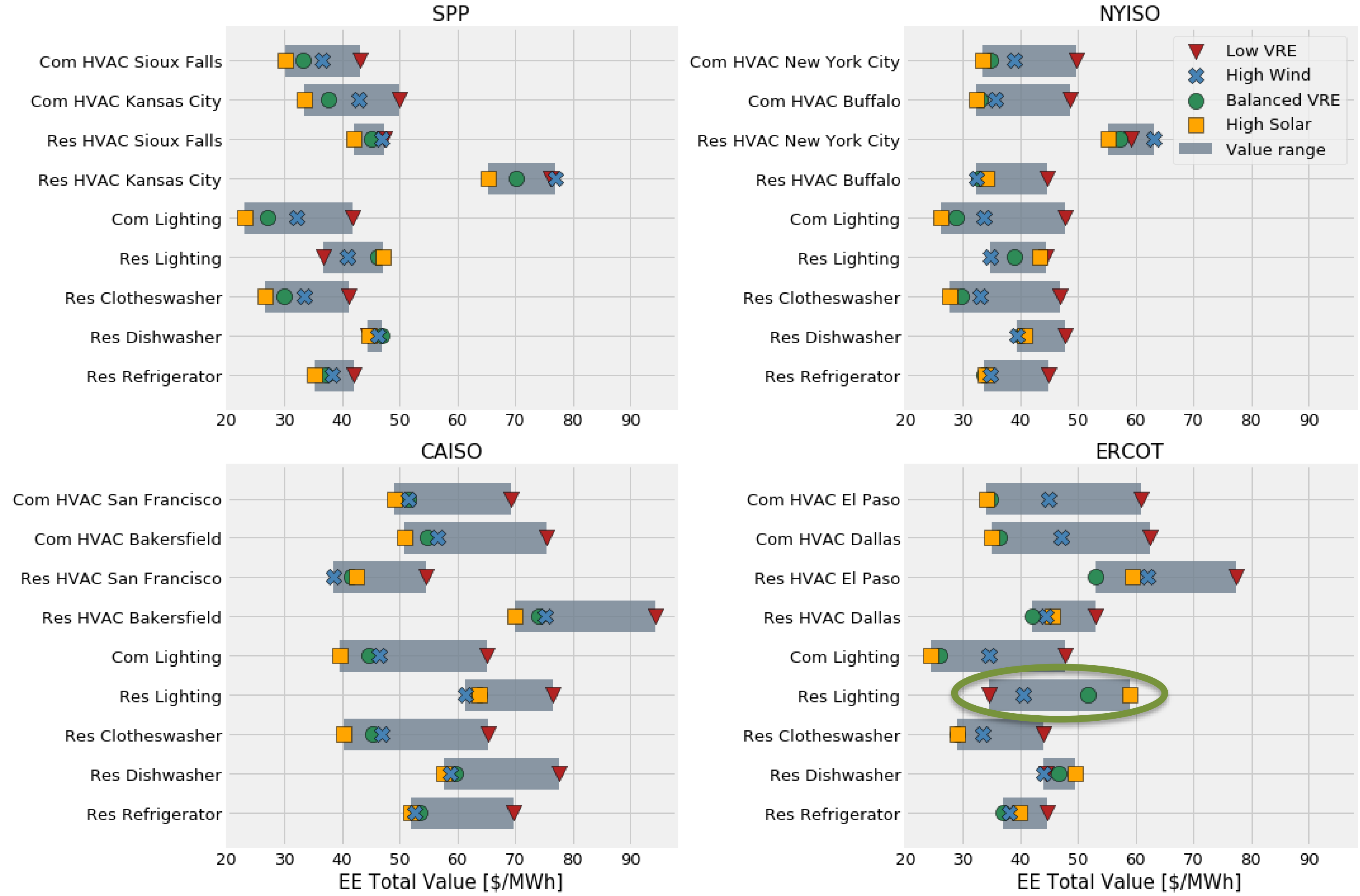


Location-dependent Load Profiles (II)



- HVAC load shapes vary significantly due to climate differences and require location-specific approach.
- 8760h profiles based on Building America Simulation reflecting TMY3 weather differences:
  - Commercial HVAC profiles include heating, cooling and fan loads in all locations.
  - Residential HVAC profiles are predominantly cooling and fan loads only, heating is assumed to be provided by gas furnaces.
    - Dallas HVAC profile also includes electric heating .
    - San Francisco profile only reflects fan loads.

EE Value Decreases for Most Measures, Driven by Strong Decline in Energy Value



- **EE value decreases for most measures and regions** with higher VRE penetrations.
  - Reduction strongest in **high solar** scenarios.
  - CAISO and ERCOT have strongest total decline.
- In SPP and ERCOT residential lighting and dishwashers **increase** in value with higher VRE.

Relative Value Ranking of Some EE Measures Changes, Especially in High Solar Scenarios

SPP

	Low VRE	High Wind	Balanced VRE	High Solar
Res HVAC Kansas City	1	1	1	1
Com HVAC Kansas City	2	4	5	6
Res HVAC Sioux Falls	3	2	4	4
Res Dishwasher	4	3	2	3
Com HVAC Sioux Falls	5	7	7	7
Res Refrigerator	6	6	6	5
Com Lighting	7	9	9	9
Res Clotheswasher	8	8	8	8
Res Lighting	9	5	3	2

NYISO

	Low VRE	High Wind	Balanced VRE	High Solar
Res HVAC New York City	1	1	1	1
Com HVAC New York City	2	3	4	6
Com HVAC Buffalo	3	4	6	7
Res Dishwasher	4	2	2	3
Com Lighting	5	7	9	9
Res Clotheswasher	6	8	8	8
Res Refrigerator	7	5	5	5
Res HVAC Buffalo	8	9	7	4
Res Lighting	9	6	3	2

CAISO

	Low VRE	High Wind	Balanced VRE	High Solar
Res HVAC Bakersfield	1	1	1	1
Res Dishwasher	2	3	3	3
Res Lighting	3	2	2	2
Com HVAC Bakersfield	4	4	4	5
Res Refrigerator	5	5	5	4
Com HVAC San Francisco	6	6	6	6
Res Clotheswasher	7	7	7	8
Com Lighting	8	8	8	9
Res HVAC San Francisco	9	9	9	7

ERCOT

	Low VRE	High Wind	Balanced VRE	High Solar
Res HVAC El Paso	1	1	1	1
Com HVAC Dallas	2	2	6	6
Com HVAC El Paso	3	3	7	7
Res HVAC Dallas	4	4	4	4
Com Lighting	5	8	9	9
Res Refrigerator	6	7	5	5
Res Dishwasher	7	5	3	3
Res Clotheswasher	8	9	8	8
Res Lighting	9	6	2	2

- Value ranking impacts stronger in high solar than high wind scenarios.
- SPP:
  - Residential lighting EE becomes much more valuable at higher solar penetrations (9. → 2.).
  - Residential HVAC EE continues to be high value option, though relative value can change depending on VRE scenario.
- NYISO:
  - Residential lighting EE becomes much more valuable at higher solar penetrations while office HVAC and lighting EE value decline.
- CAISO:
  - In CA most of the solar-induced relative shifts among EE measures have already occurred in the low VRE scenario (with 14% solar).
- ERCOT:
  - Office HVAC and lighting EE value decreases in relative value with higher solar scenarios.
  - EE value differential moderate in High Wind while steeper in High Solar → discrete scenario analysis valuable.

Opportunities for Large Energy Consumers

VRE Impacts on Industrial End Uses- Overview of Issue

- For energy-intensive industries, changing energy price dynamics in high VRE futures may offer opportunities to refine production processes – profiting from periods with low or negatively priced electricity.
- Method: **Minimize a product's levelized unit-cost**
  - Capital costs and maintenance costs (scaling with production capacity).
  - Operating costs (scaling with production volume, lowered by higher process efficiencies).
- Evaluating opportunities for increased technical and financial (capex vs. opex shares) flexibility.
  - Changes in optimal utilization rates:
    - **Hydrogen Production and other electro-commodities**
  - Product storage enables higher production output at low prices:
    - **Desalination Projects**
  - Supplementary production processes enable fuel-switching flexibility:
    - **District Energy Systems** with gas-boilers and electric heat-pumps

Case Study 1:
Power-to-H2

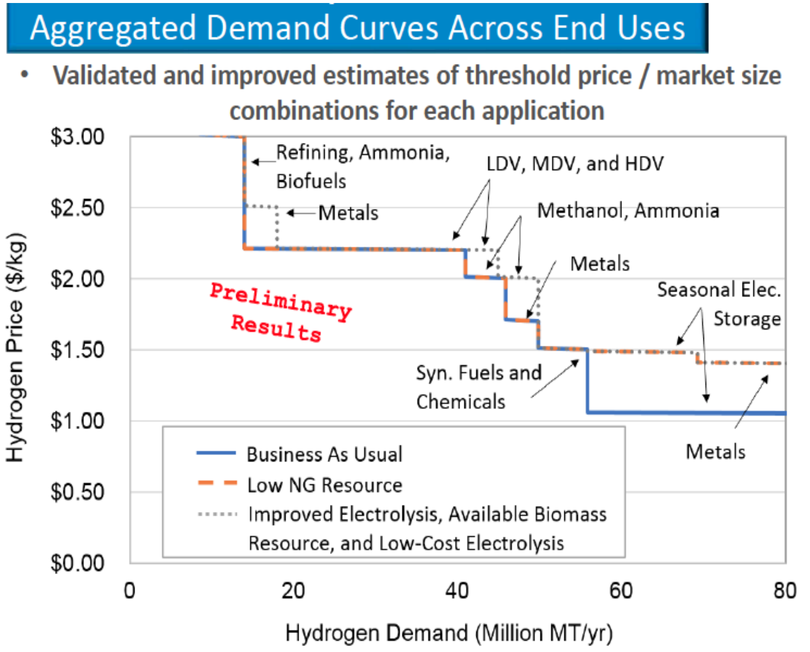
Power-to-Hydrogen is Currently a Niche Application due to High Production Costs

- Background:
  - Power-to-Hydrogen as example for general P2X processes, analytical method can be extended to other applications.
  - H2 can be used in fuel cells or for production of ammonia, fertilizer, syn-gas, methanol...
  - Hydrolysis process with an alkaline electrolyzer – an energy-intensive process where electricity costs are usually the dominant cost factor.
  - Most hydrogen production is currently based on natural gas (6% of global natural gas demand) and coal (2%).

Case Study: Stylized Hydrogen Plant

- 10MW plant
- Capex: $650/kW installed cost
- 70% process efficiency
- 4% maintenance costs
- 25 year lifetime (10 year amortization)
- 6% WACC
- cell stack replacement after 60,000h at 25% Capex

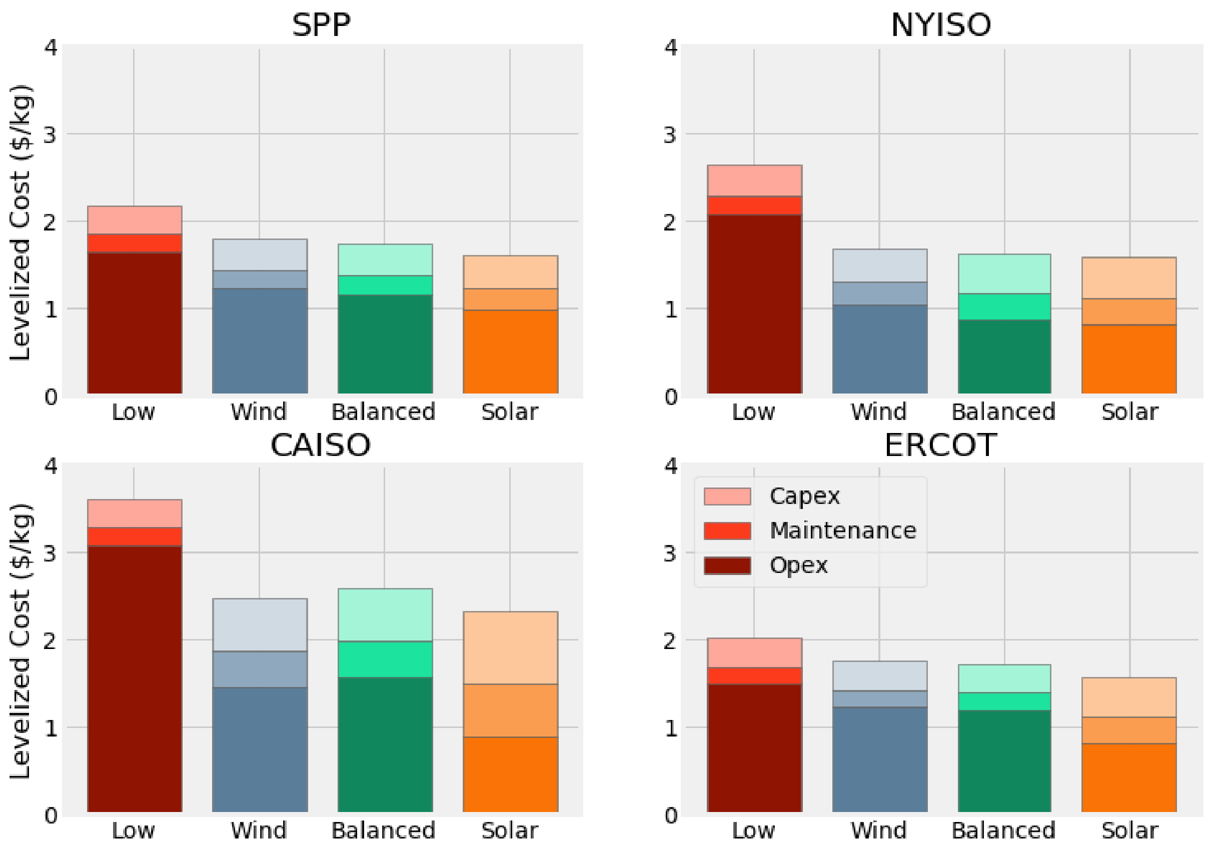
Focus on production costs, excluding costs associated with gas compression + distribution.

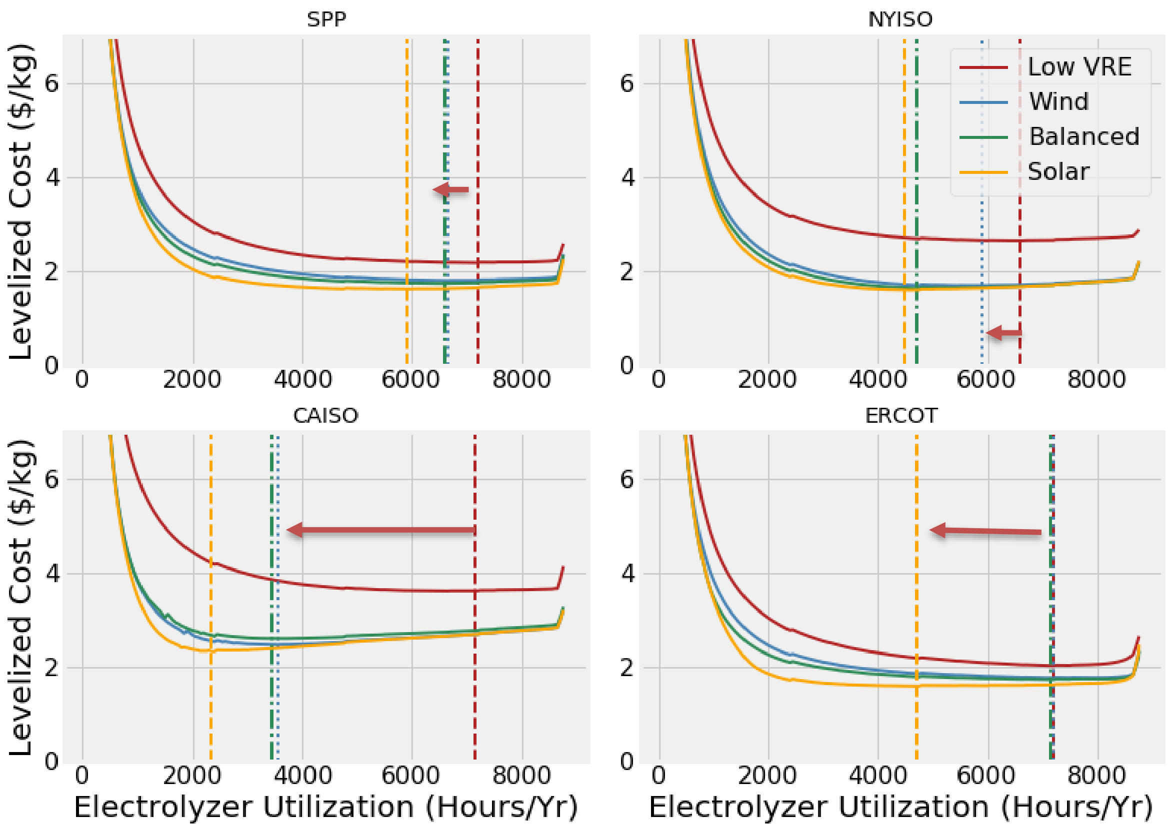


Source: Ruth et al., 2019, “H2@Scale”

High VRE Futures Can Lower H2 Production Costs

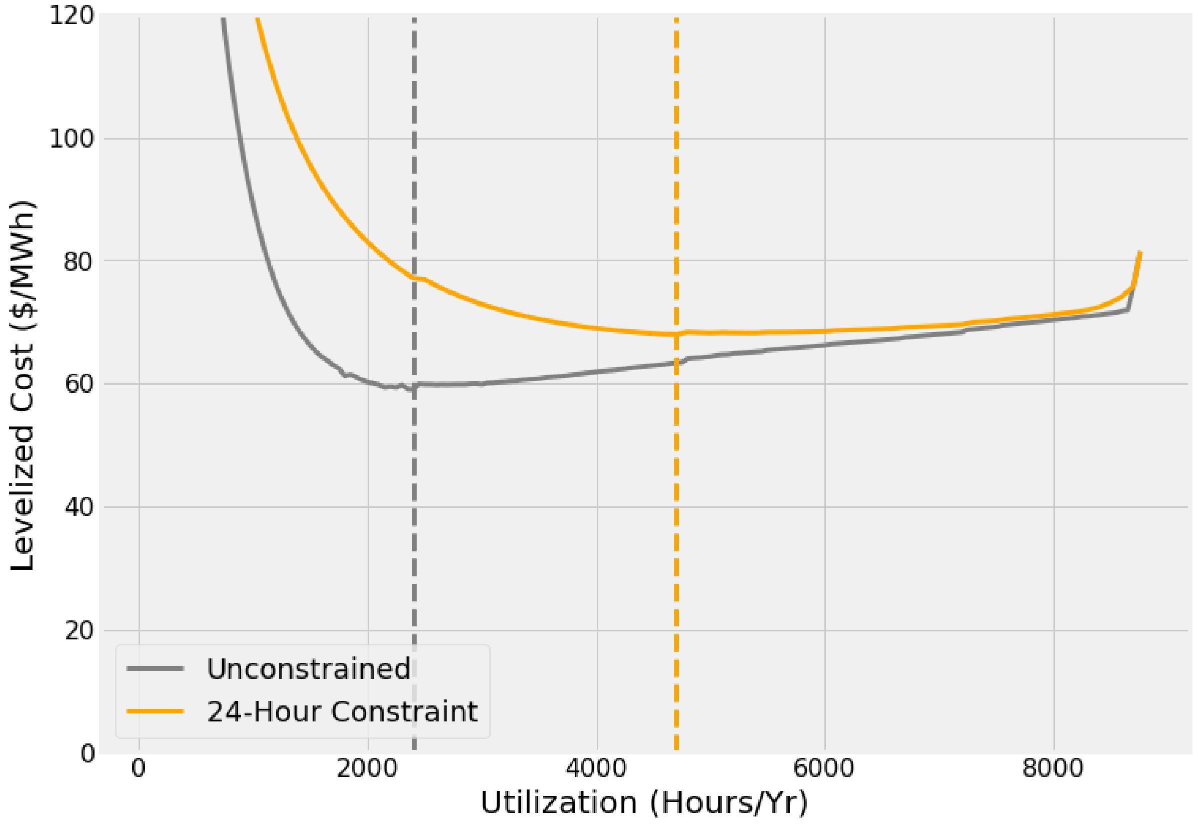
- **Low-priced electricity in high VRE scenarios can reduce dominant operating costs**, leading to total cost reductions of 13-40%.
- NYISO/CAISO include carbon costs in wholesale electricity prices.
- Utilization rates in the low VRE future range from 75 to 82% compared with 27 to 82% in the high VRE futures.
- Larger opportunity for Capex reductions (e.g. CAISO **solar**).

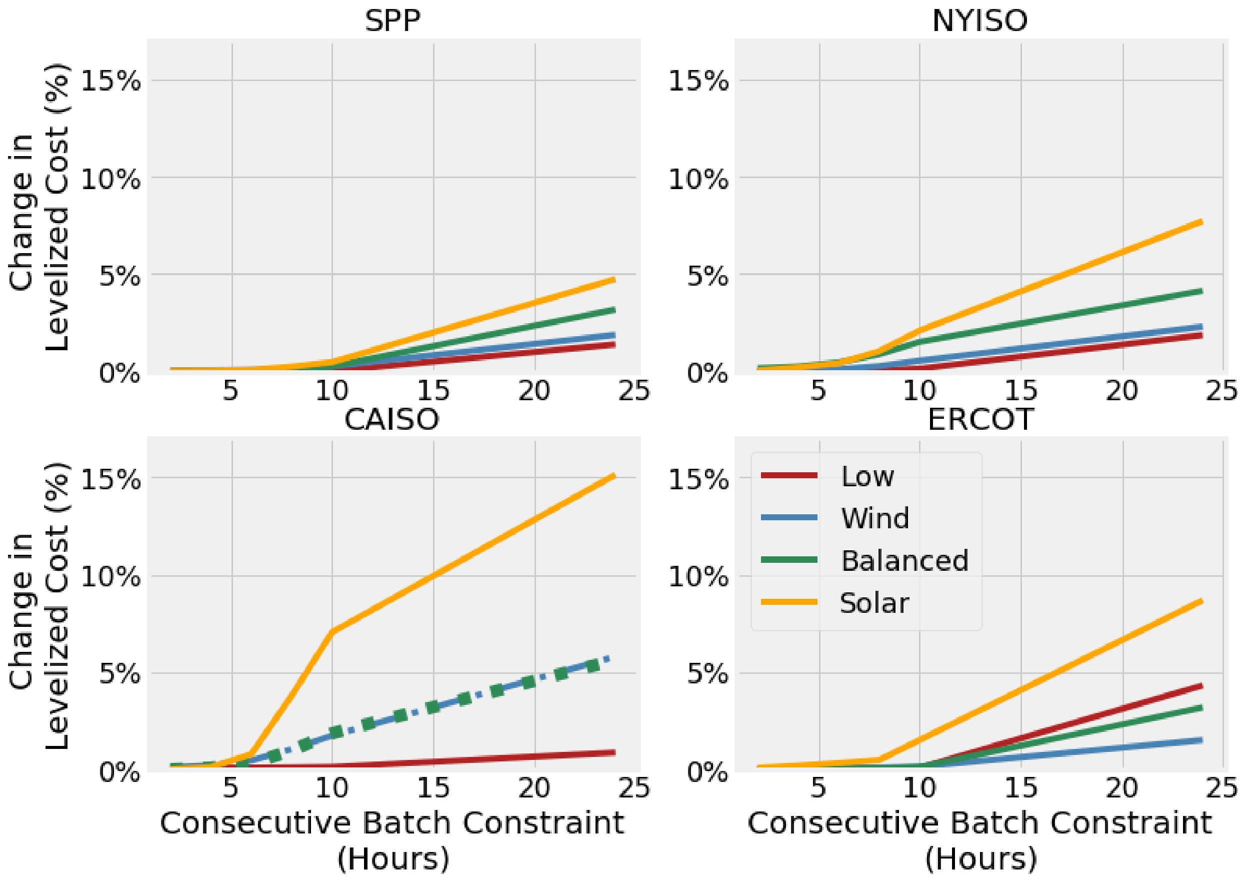




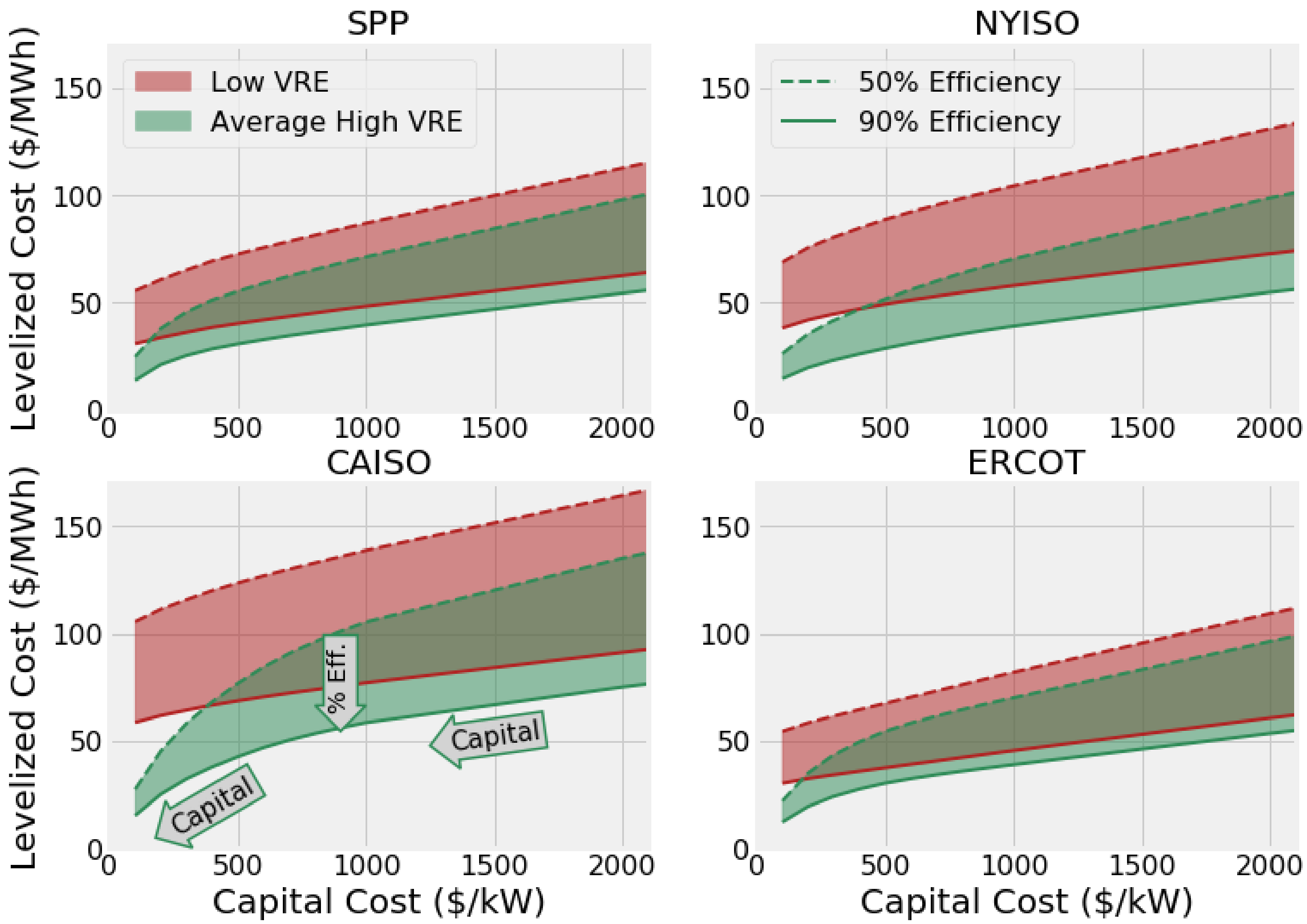
Batch Constraints for Other Electro-Commodities Reduce Opportunities to Focus Only on Low Price Periods

- Batch constraint of 24 hours leads to higher utilization and higher costs.
- Constraints most impactful with High Solar.





High VRE May Shift R&D Focus for Electro-Products from Process Efficiency Improvements to Capex Reductions



- Cost curves show low (- -) and high (—) efficiency processes in a low and average high VRE scenario.
- Capital cost intensive industries are less sensitive to VRE futures (right end).
- Gain from improving efficiency is smaller in high VRE futures (moving downward).

Case Study 2: Desalination

Adding Storage to Desalination Systems to Increase Operational Flexibility

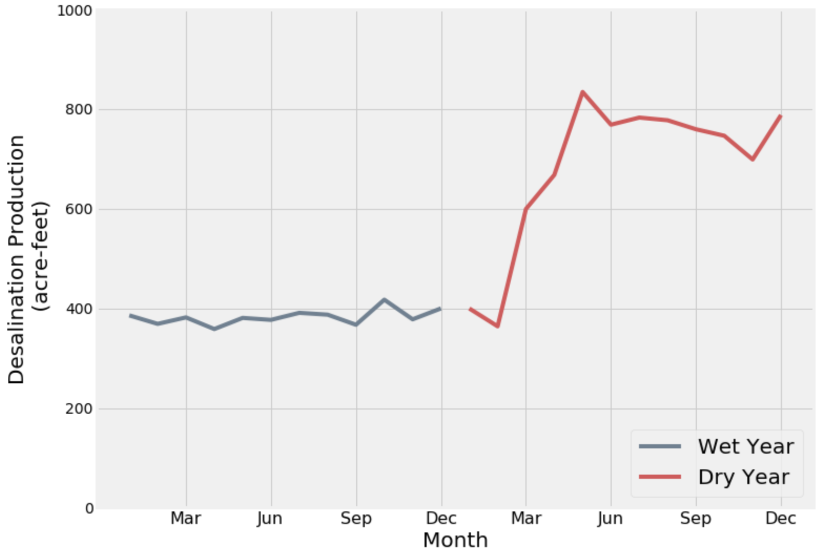
- Background:
  - Water desalination with reverse osmosis is an energy-intensive process, employed throughout the U.S., not just for ocean water but also brackish ground water.
  - With increased storage reservoirs, water desalination plants can increase production during hours with low electricity prices and dispatch at hours with high electricity prices.
  - Trade-off: Additional capital investments in storage vs. lower operating costs.

Case Study: Largest U.S. in-land desalination project

Kay-Bailey Hutchingson in El Paso, TX

- Currently operates below maximum capacity for most of the year
- Hourly water demand set externally by El Paso Water Authority
  - Contrasting wet year with dry year, the latter requiring additional water delivery
- Product storage costs for clean water (building water reservoirs @ $1000/acre-foot) is low relative to storing electricity used as process-input

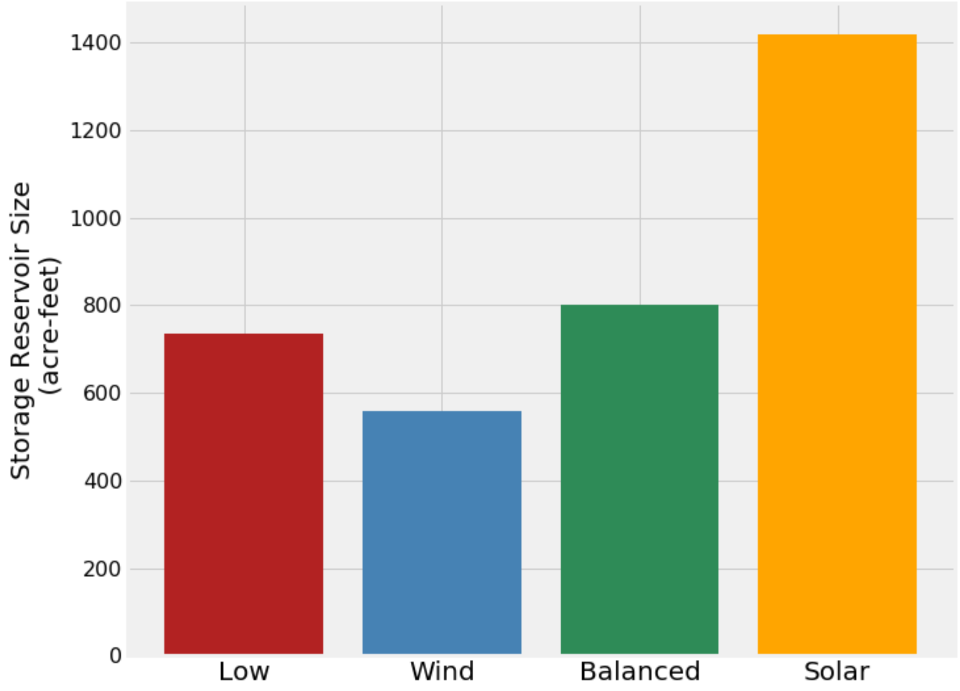
Desalination water demand in El Paso

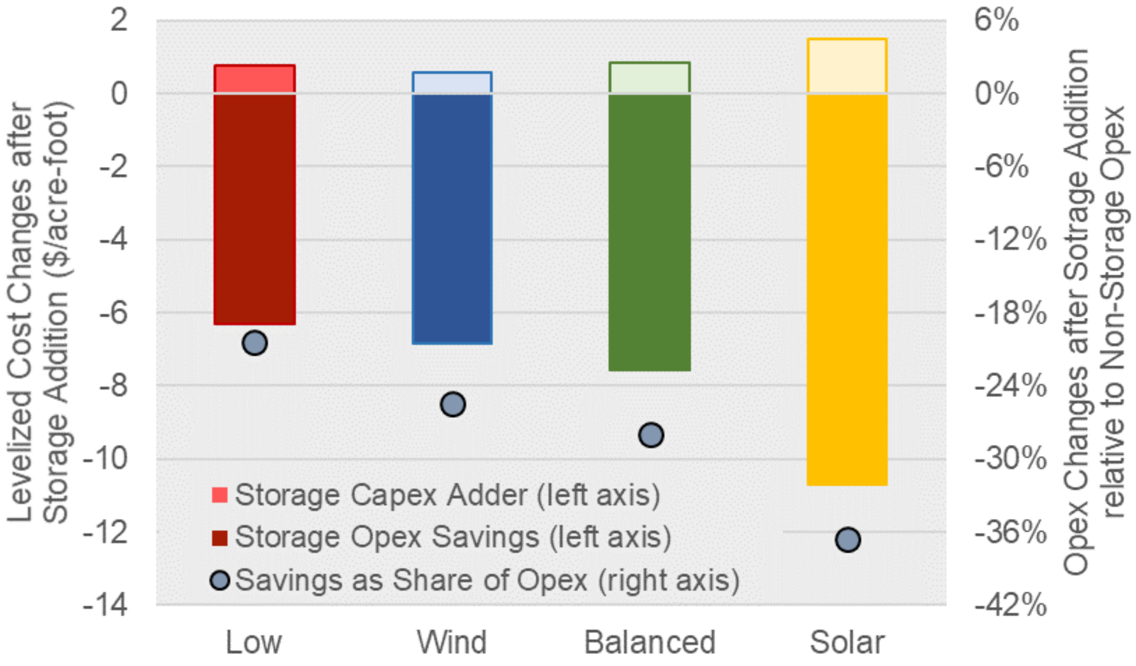


Case Study 2: Desalination

Storage systems become larger, are used more often, and allow for more savings in high VRE scenarios

- Water storage additions are cost-effective in all scenarios.
- Optimal water storage **size** and storage **utilization hours** increase with near-zero electricity cost hours, especially in **solar** scenario (+93% and +134% of hours).
- Overall unit costs of delivered water decrease modestly in high VRE future as Capex is dominant in brackish desalination applications.
- Focusing only on marginal expenses, water storage addition offers higher savings in high VRE scenarios (37% Opex reduction in **solar** scenario).

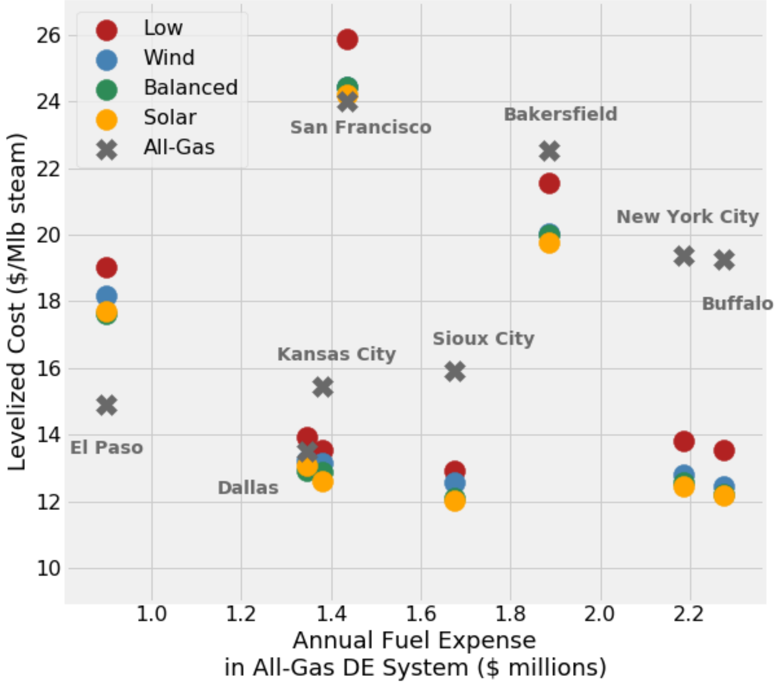




Case Study 3:
District Energy System

Adding Heat Pumps to District Energy Systems to Increase Flexibility

- Background:
  - Most district energy systems rely on fossil fuels as main energy source for district heating (and occasionally cooling), sometimes in the form of combined-heat-and-power.
  - Up to 5800 systems in the U.S., many on college campuses, office parks or urban clusters.
  - Trade-off: Additional capital investments in industrial-scale heat-pumps (HP) enables lower operating cost due to fuel switching at times of low electricity prices.
  - Increased complexity: time-varying fuel costs, time-varying demand for heat is not flexible.



Stylized college campuses around the U.S.

- Comparing all-gas system with electric hybrid system (20% heat pump)
- 2 locations per ISO → different load shapes based on *Build America Simulation* for school + apartment buildings
- Capex: Natural gas boilers: $120/kW, heat pump $800/kW
- Heat pump *Coefficient of Performance:* 5
- Varying natural gas costs by month and region (carbon fee in CA, NY)

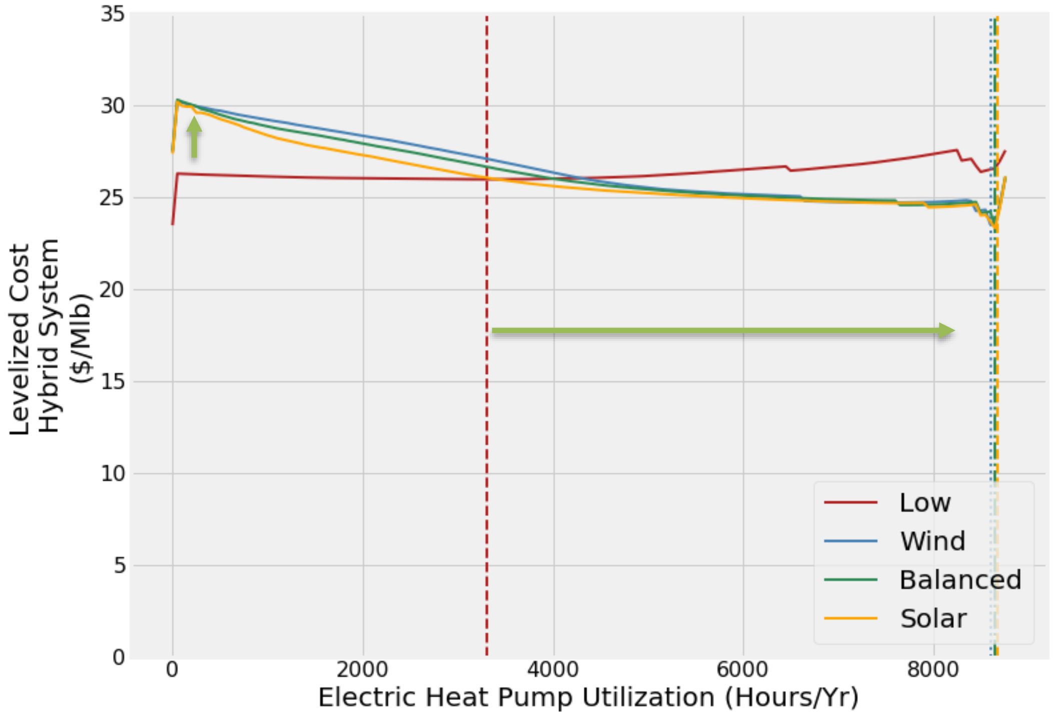
- Findings:
  - Hybrid systems perform worse in locations with low annual natural gas expenses, but better in regions with higher expenses.
  - Even in low VRE future a highly efficient heat pump outperforms natural gas boilers, effect is even stronger in high VRE futures.
  - Performance differences are highest in CA and NY (carbon prices) and lowest in TX (cheap gas).

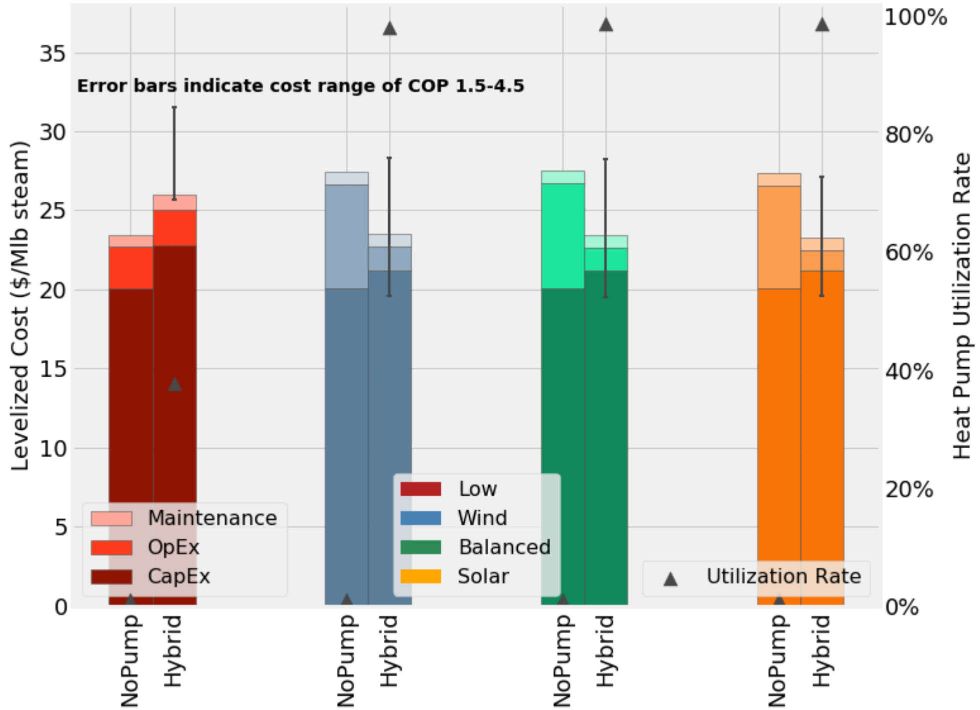
Case Study 3:
District Energy System

Flexibility Option Lowers Costs only in High VRE future in Manhattan Case Study

World's largest district energy system by ConEd in Manhattan

- winter-peaking system with maximum demand of 8MMlb steam/h
- Legacy system: 60% natural gas boilers, 40% cogeneration
- Monthly varying natural gas costs $4.6-6/MMbtu (incl. carbon price)
- Heat pump *Coefficient of Performance:* 3





- In high VRE scenarios cogeneration revenue decreases due to lower electricity prices → Opex for all-gas systems increase.
- Cost-optimal utilization rises in high VRE scenarios.
- Hybrid system decreases levelized costs only in high VRE scenarios by -$5/Mlb steam (**low VRE**: +$3/Mlb steam).

Retail Rate Design

VRE Impacts on Rate Design – Overview of Issue

- Key questions
  - Under different high VRE future scenarios, how might regulated retail electricity rates further diverge from marginal cost and how does this impact economic efficiency?
  - What new aspects should retail rate designers consider when drafting the next generation of rates?

- Economic efficiency will be weighed against other rate design principles.
  - Fairness, simplicity, bill/revenue stability, customer acceptance, and others.

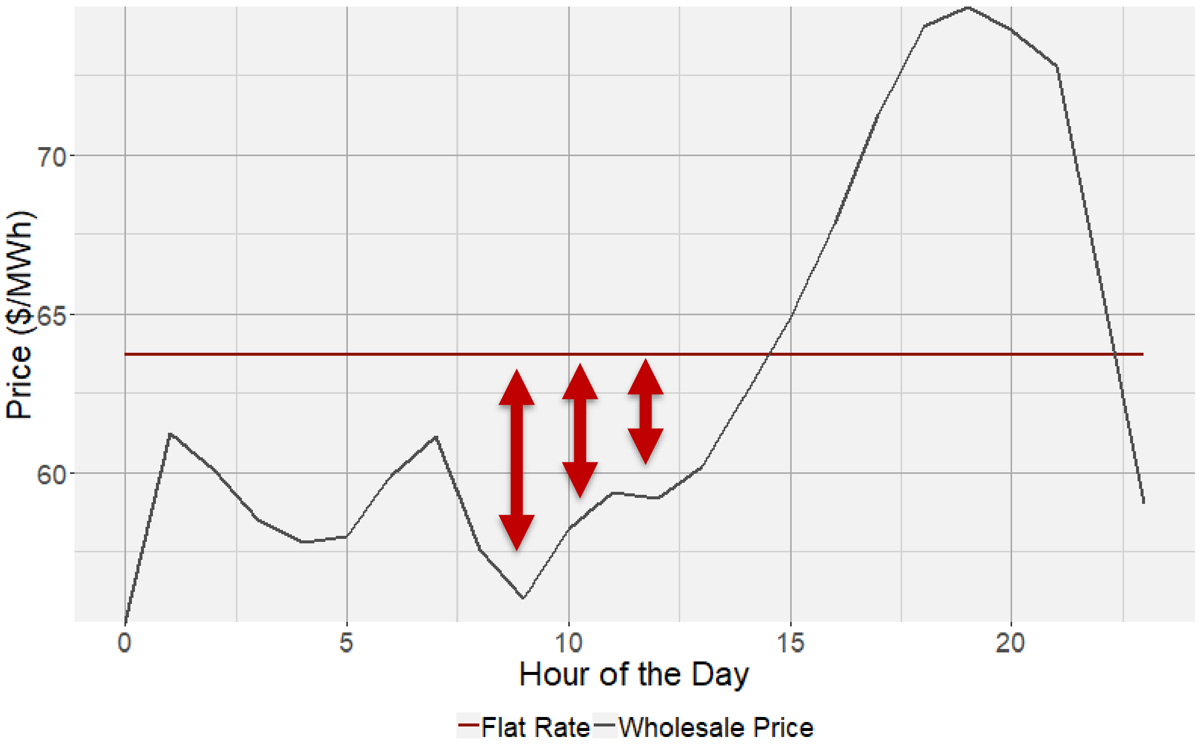
Rate Design Analytical Framework

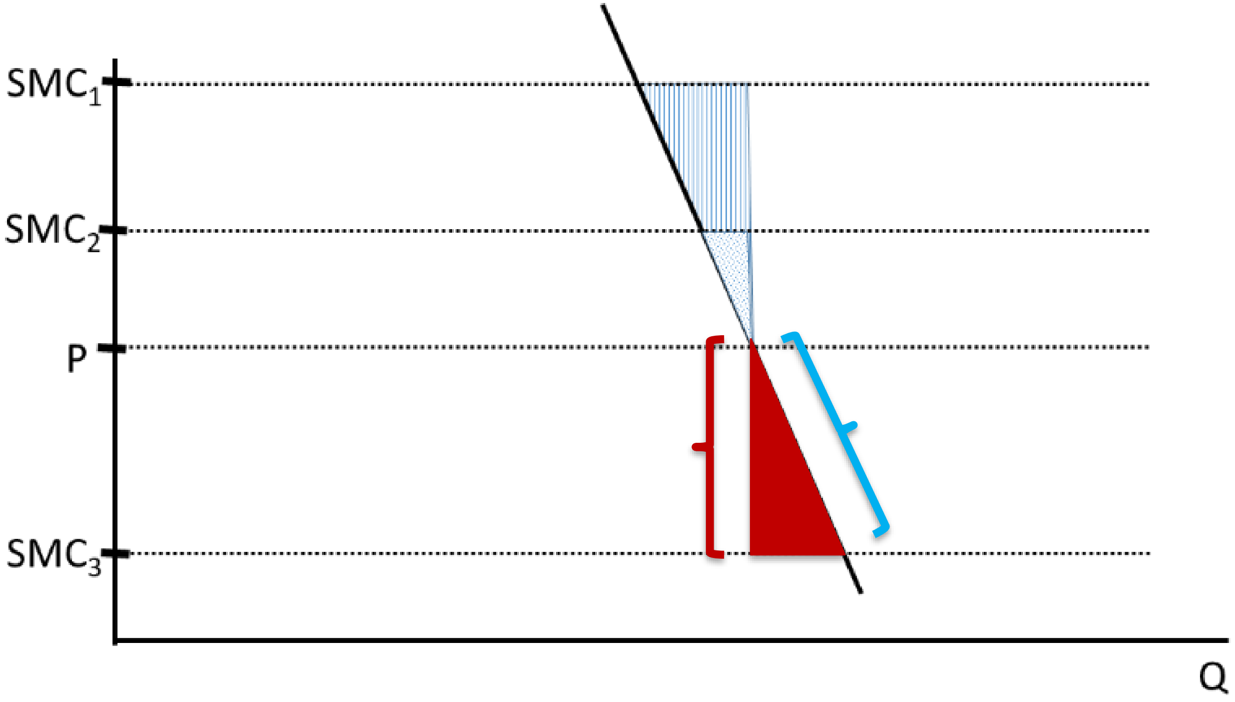
Method: Maximize economic efficiency by **minimizing deadweight loss (DWL)**

1. Design rates that minimize DWL in a low VRE future.
2. Project low VRE rates on high VRE futures and quantify DWL changes.
3. Redesign rates to minimize DWL in high VRE futures.

	Rates	Wholesale Energy Prices
1.	Low VRE	Low VRE
2.	Low VRE	High VRE
3.	High VRE	High VRE

Deadweight Loss Explained



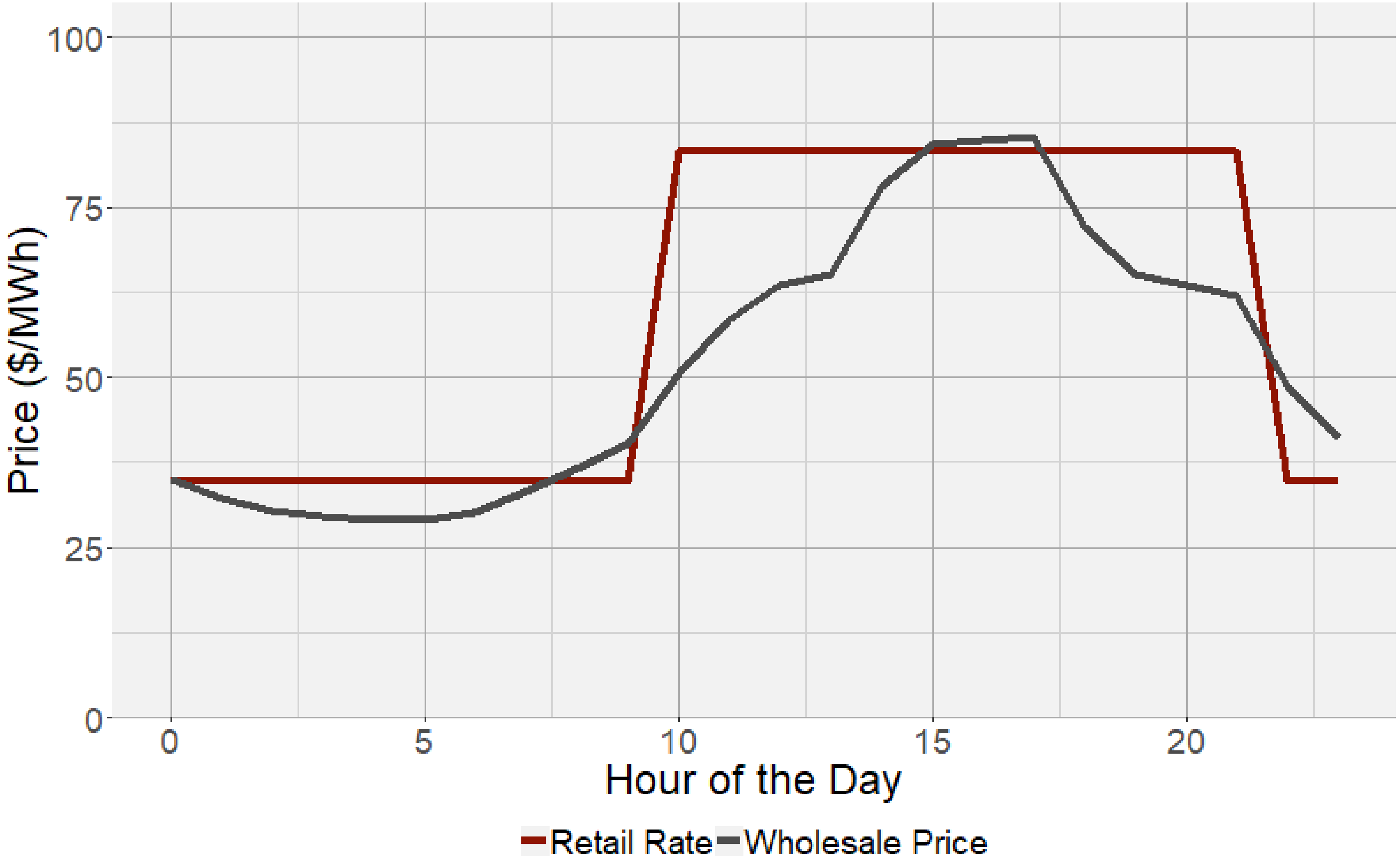


Deadweight Loss (DWL) will be used throughout the presentation and will be used interchangeably with "economic inefficiency"

$$DeadweightLoss_{iso} = \frac{1}{2\hat{s}}\left[\sum_{h=1}^{H} Q_h * \left(P_h^{rate} - P_h^{wholesale}\right)^2\right]$$

1. Low VRE Optimization

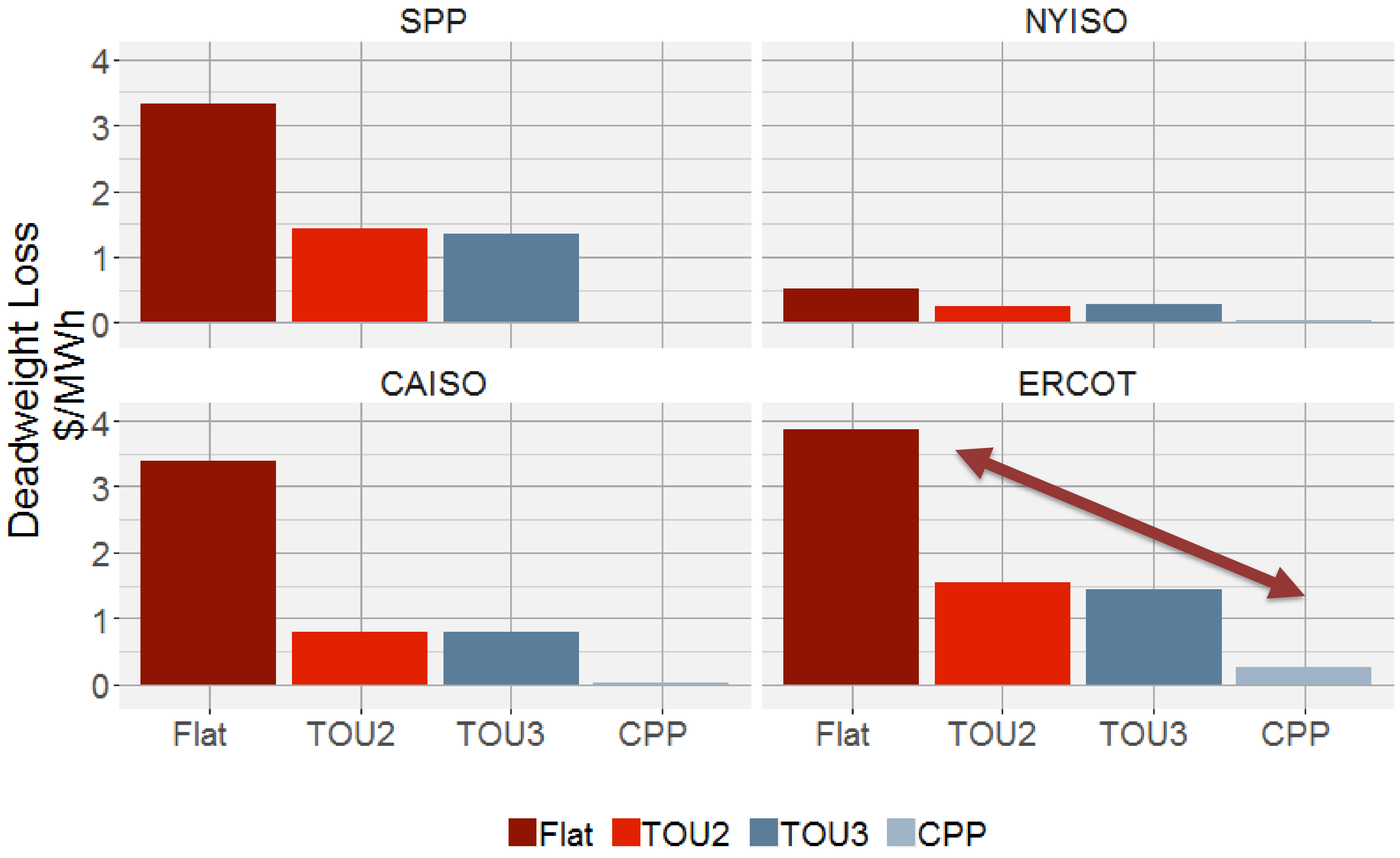
2-Period TOU:
Peak Periods Resemble Today's TOU Rates



Rate Characteristics	
Rate Structure	2-Period TOU
Season	Summer
ISO	NYISO
Scenario	**LowVRE**

1. Low VRE Optimization

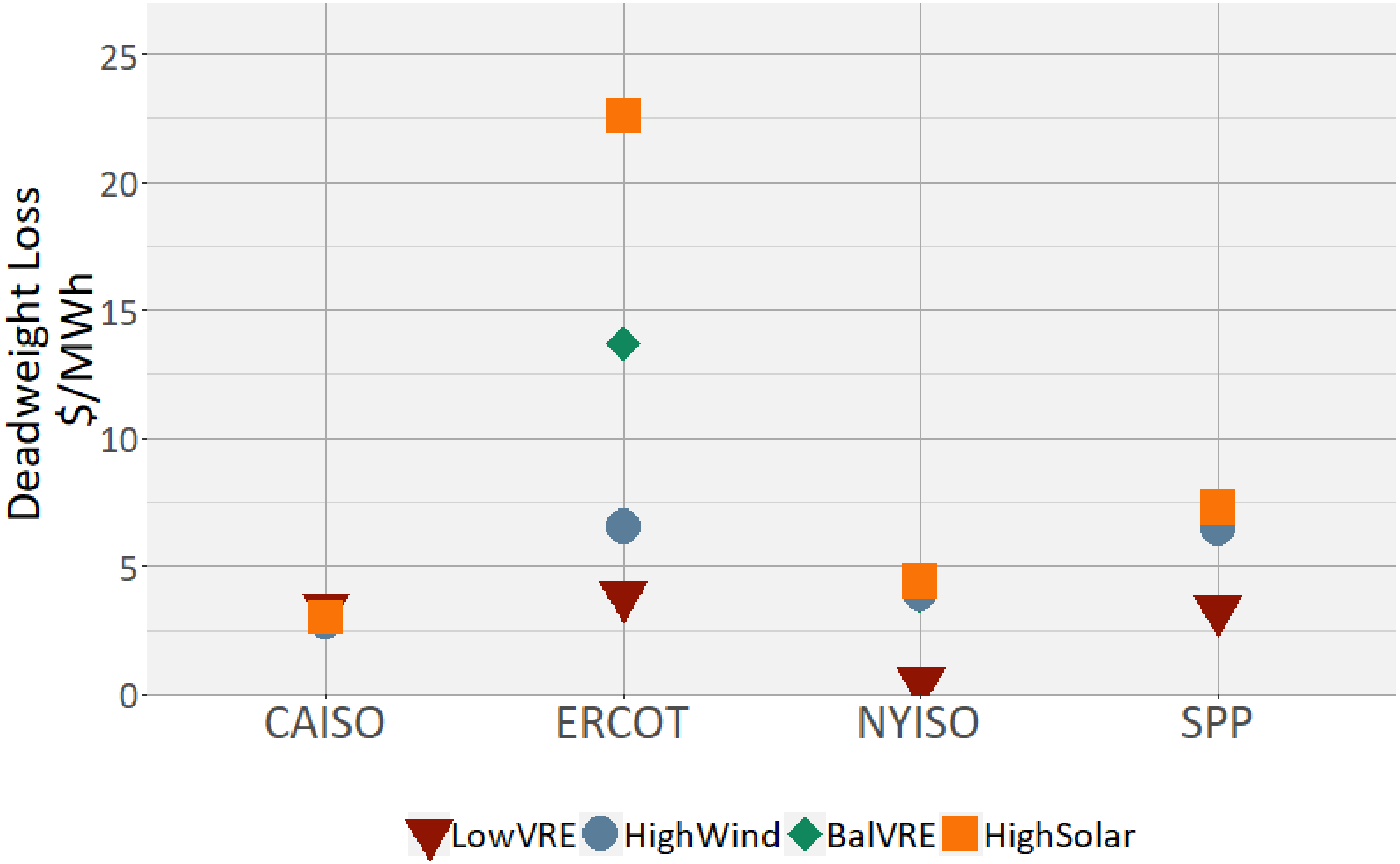
Time-Differentiated Rates Are More Efficient Than Flat Rates



- DWL decreases with closer approximation of Real-time Prices (RTP).
- Annual DWL across all hours of year ranges from a low of *$3m* on a CPP rate to a high of *$2b* on a flat rate.

2. Low VRE Rates With High VRE Prices

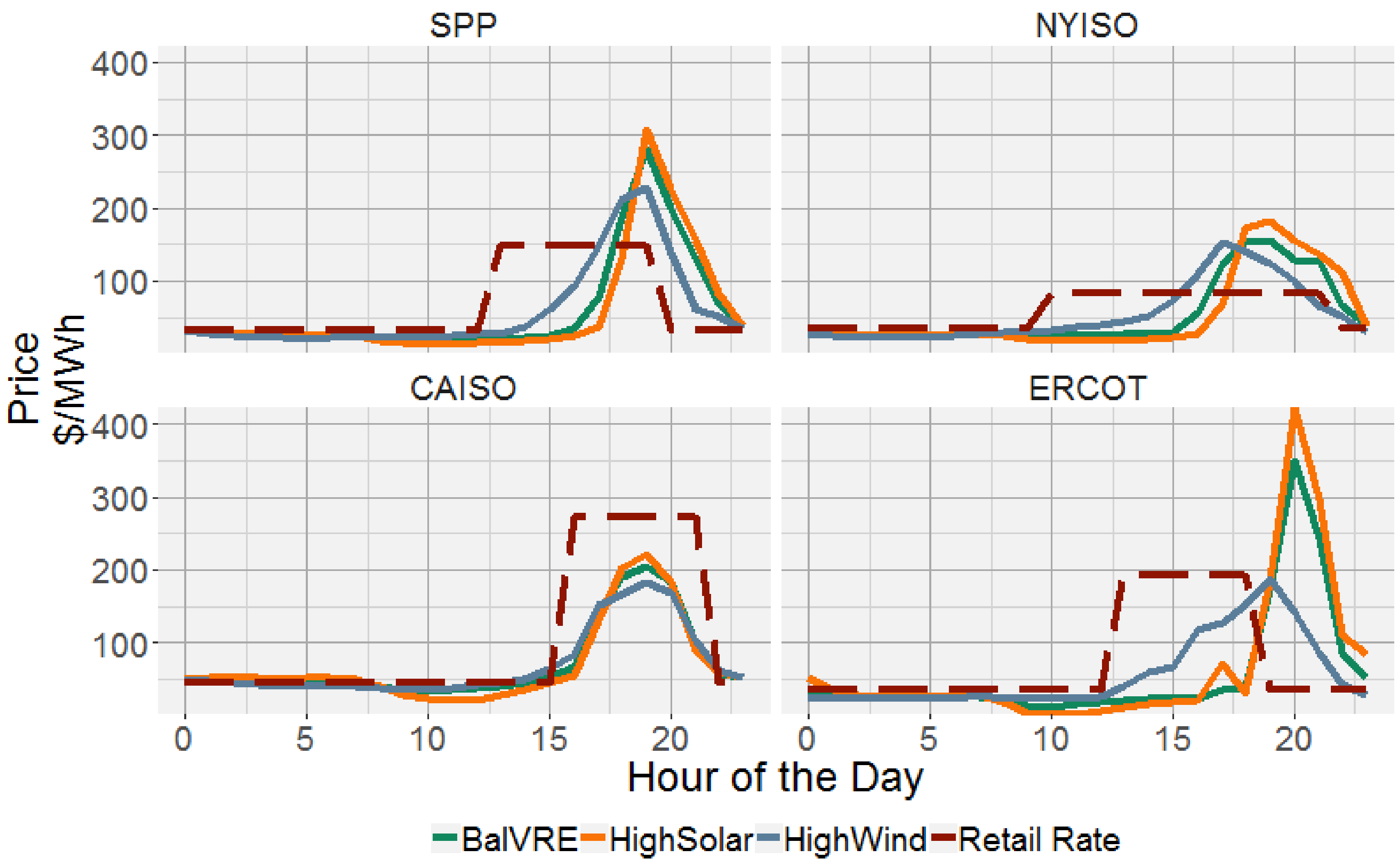
Flat Rates Cannot Capture Increased Price Volatility



- Inefficiency of flat rates may be tolerable with low VRE penetration but economic losses increase with growing VRE shares.
  - Losses are large in ERCOT and minimal in CAISO (low VRE already has duck curve).

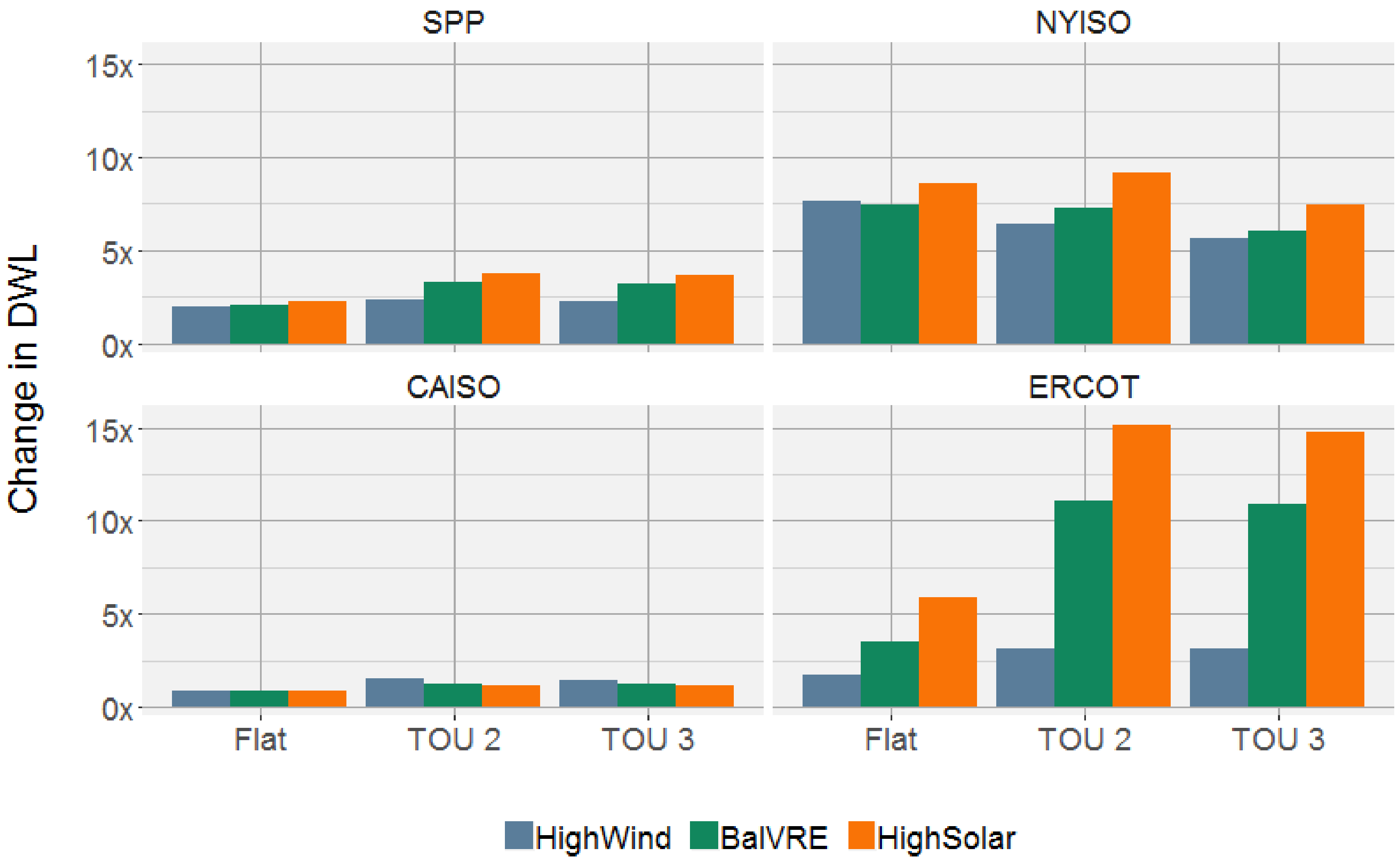
2. Low VRE Rates With High VRE Prices

2-Period TOU:
Mistiming of Peak Period in HighVRE



Rate Characteristics	
Rate Structure	2-Period TOU
Season	Summer

LowVRE Rates in HighVRE Futures:
Not Adjusting Rates Leads to Higher Losses

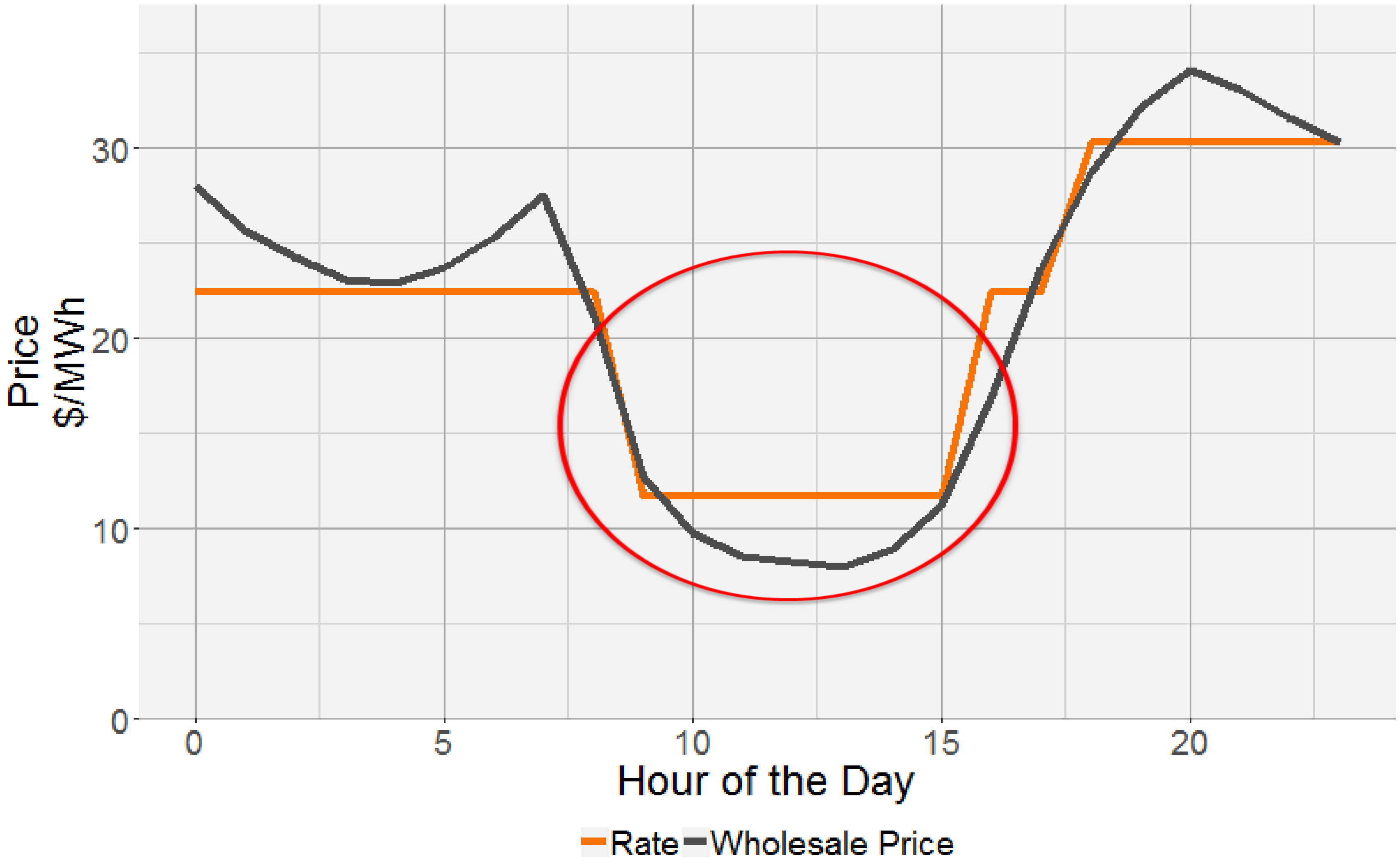


- Substantial increase in DWL, particularly in NYISO and ERCOT.
- Mistiming of peak period contributes to high DWL.
- TOU periods relatively well-aligned in CAISO.

3. High VRE Optimization

3-Period TOU:

Super-Off Peak is Efficient in HighSolar Future



Rate Characteristics	
Rate Structure	3-Period TOU
Season	Winter/Spring /Fall
ISO	SPP
Scenario	High Solar

3. High VRE Optimization

Redesigning LowVRE Rates:
Time-Varying Rates are More Valuable in High VRE Future

- Time-varying rates offer greater efficiency improvements in high VRE futures.
- CPP programs layered with TOU offer the most improvements to economic efficiency.
- Greatest benefits of time-varying pricing in ERCOT.

Conclusion: Energy Efficiency

- Forward-looking scenario analyses that leverage time-dependent valuation approaches can provide insights about resource trade-offs under high VRE scenarios:
  - Absolute values and relative ranking of EE measures will change with higher VRE penetrations.
  - High wind scenarios can increase irregular hourly price volatility but can moderate average diurnal price profiles over longer → value differences may flatten.
  - High solar scenarios have a strong effect on diurnal price profiles → value differences may increase.

- In high VRE scenarios, residential EE upgrades that lower evening consumption seem to deliver higher value savings than office EE upgrades that provide daytime savings.

  → residential EE upgrades could be targeted in future program design.

- Future research may:
  - Evaluate broader set of measures, more robust EE saving shapes, and additional value streams.
  - Include measure cost in analysis.

Conclusion: Opportunities for Large Energy Consumers

- Large energy consumers can benefit from changing electricity price dynamics and increased frequencies of very low price events if they can access wholesale electricity markets and if they can substitute electricity for other energy inputs in their production processes.

- Large energy consumers who will benefit most from periods of low electricity prices in high VRE scenarios are those that:
  - have energy-intensive processes such that energy costs are high relative to the capital costs of production equipment (e.g., electro-commodities).
  - can effectively decouple commodity production from demand by increasing intermediate or final product storage capacity.
  - can invest in the capability to switch between fuels and electricity during periods of low electricity prices.

- Future research might explore:
  - how relative R&D investment requirements to reduce either the capital cost of relevant equipment or yield higher process efficiencies compare with the changing cost-reductions in high VRE scenarios.
  - the potential for electricity to provide higher temperature heat for industrial applications.
  - how industrial production schedules can be modified to increase flexibility in their electricity consumption in response to more dynamic electricity prices.
  - how low VRE prices would affect location decisions about new production plant investments, technology choices within a given industry, and electricity market dynamics if demand grows during low cost periods.

Conclusion: Retail Rate Design

- Aligning retail rates more closely with marginal cost can increase overall demand responsiveness to varying system needs.
- More dynamic retail electricity rates have lower economic losses than flat rates, and their relative benefit increases with higher VRE penetrations → More serious deliberation of complex rate structures.
- Growing wind and especially solar shares impact the best definition of peak versus off-peak periods.
  - High versus low price periods defined for a low VRE environment can lead to even worse outcomes than maintaining flat rates when applied without changes to a high VRE environment.
  - Appropriately calibrated retail rates with a new super-off peak period in the middle of the day can bring large efficiency gains in a high solar scenario.
- Further research might assess:
  - How residential, commercial, and industrial customers might capture more economic value from rate design in a high VRE scenario.
  - Consider impacts of T&D costs on rates in various future VRE scenarios.

Thank you for your attention!

For questions and feedback:

Joachim Seel:

jseel@lbl.gov 510-486-5087

Andrew Mills:

admills@lbl.gov 510-486-4059

Download all of our other solar and wind work at:

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Follow the Electricity markets & Policy Group on Twitter:

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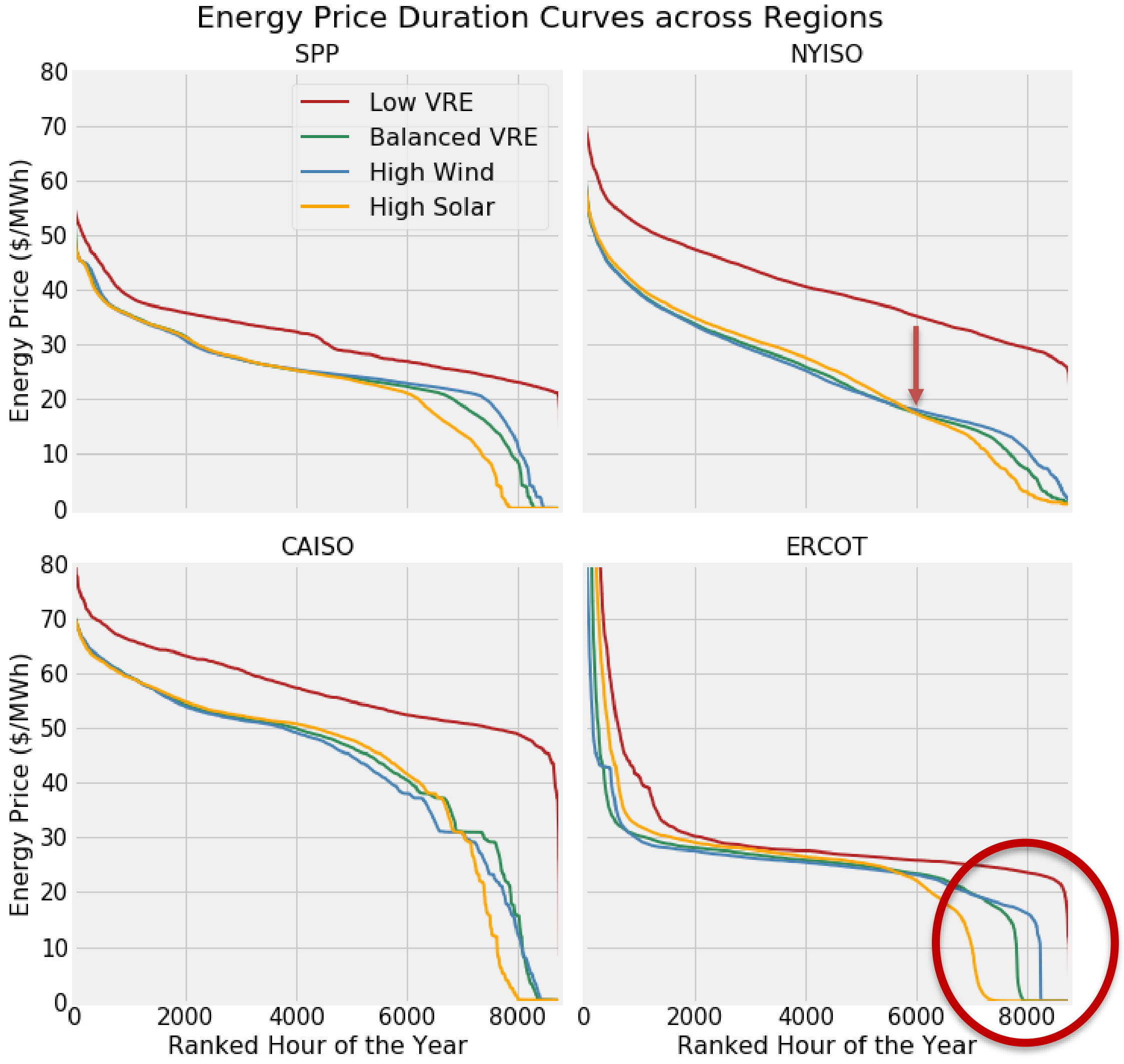
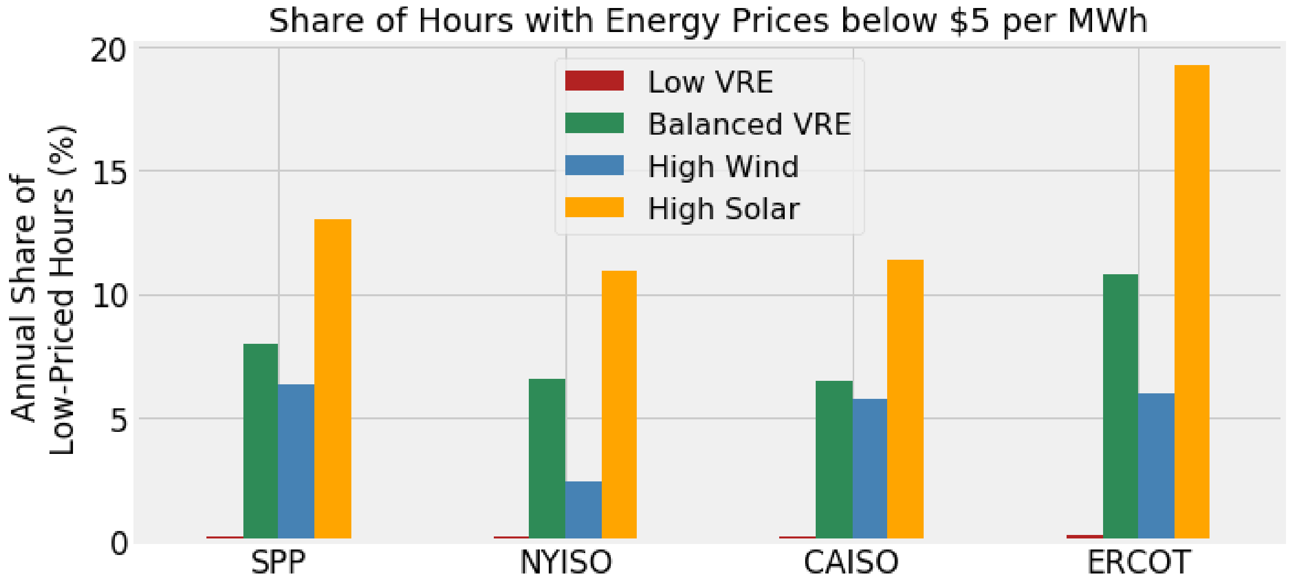
Low Energy Prices Become More Frequent Under High VRE Scenarios





- In some regions, the shape of the price distribution curve does not change dramatically but is merely shifted downwards (e.g. NYISO)
- Other regions feature a more pronounced 'cliff', featuring a dramatic increase in hours with very low prices (e.g. ERCOT)
- Low prices driven by **solar** more than **wind**