Impacts of High Variable Renewable Energy (VRE) Futures on Electric-Sector Decision Making:

Options for Industrial End-Users

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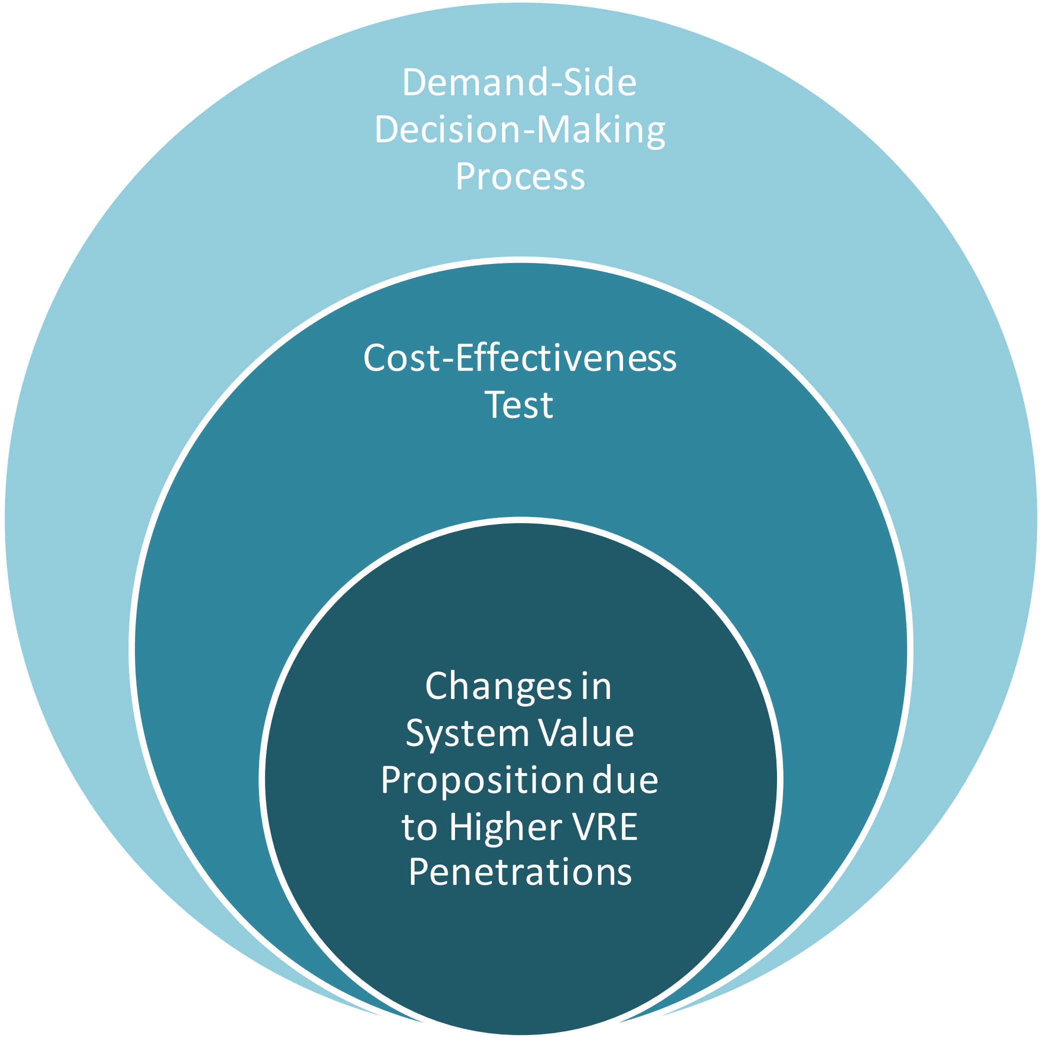
Project Overview

- Many long-lasting decisions in the electricity sector are made based on historical observations or a business-as-usual future. As the variable renewable energy (VRE) share increases, however, **fundamental characteristics of the power system will 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. Focus today is on industrial end-uses.

Relevance of System Value Changes for Demand-Side Decisions



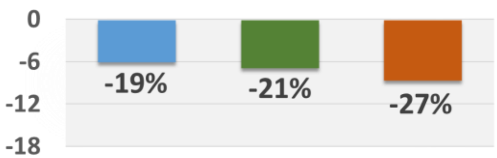
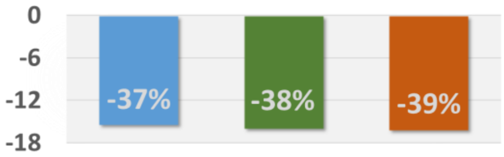
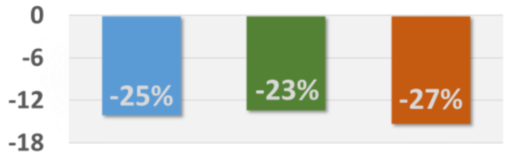
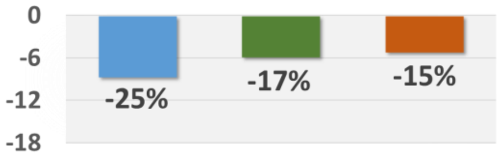
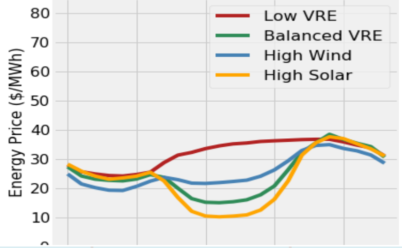
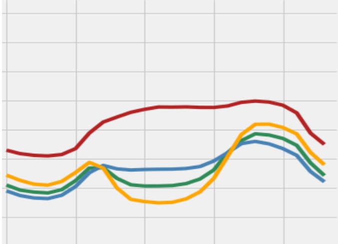
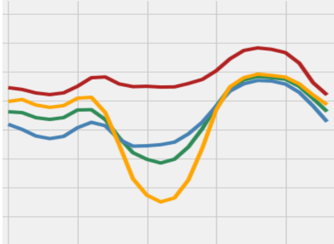
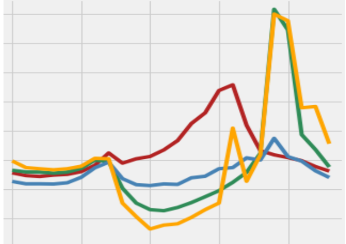
◆ Decisions about demand-side programs or investments are complex and incorporate many considerations, including economic efficiency, equity, or specific policy goals (e.g. increasing EV adoption).

◆ 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 plan to leverage our 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		

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Value Streams Considered in our Analysis

- Focus thus on broad directional changes that policy makers should consider
  - ❑ no full replication of total cost-effectiveness tests

- Limitations of our analysis:
  - ❑ Insufficient data for all value streams
  - ❑ Marginal value assessment only (no feed-back loops)
  - ❑ Limited scenario analysis
  - ❑ Only modeled single year, may not be representative of longer-term system evolution

Value Streams considered in Value analysis

Included
- Energy
- Generation capacity
- Internalized environmental costs

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

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 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)

- Analysis of 3 exemplary production-related investment decisions via case studies:
  - ❑ Investments in **new** stand-alone processes:
    - **Power-to-X**
  - ❑ Investments in supplementary production processes enabling fuel-switching **flexibility**:
    - **District Energy Systems** with gas-boilers and heat-pumps
  - ❑ Investments in product **storage**, enabling higher production output at low prices:
    - **Desalination Projects**

Case Study 1:
Power-to-H2

Power-to-Hydrogen is Currently Niche a 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. Still in pre-commercial phase.
- Most hydrogen production is currently based on natural gas (6% of global natural gas demand) and coal (2%).

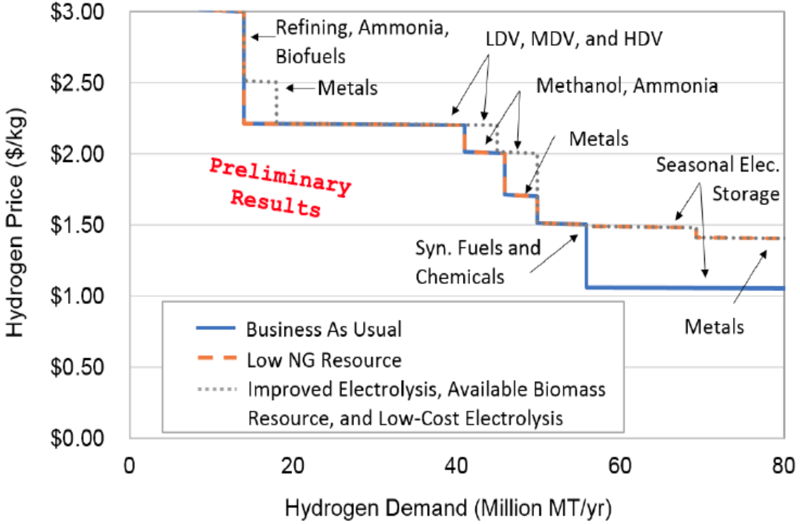
Case Study: Stylized Hydrogen Plant

- 10MW plant
- Capex: $1000/kW
- 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

Aggregated Demand Curves Across End Uses

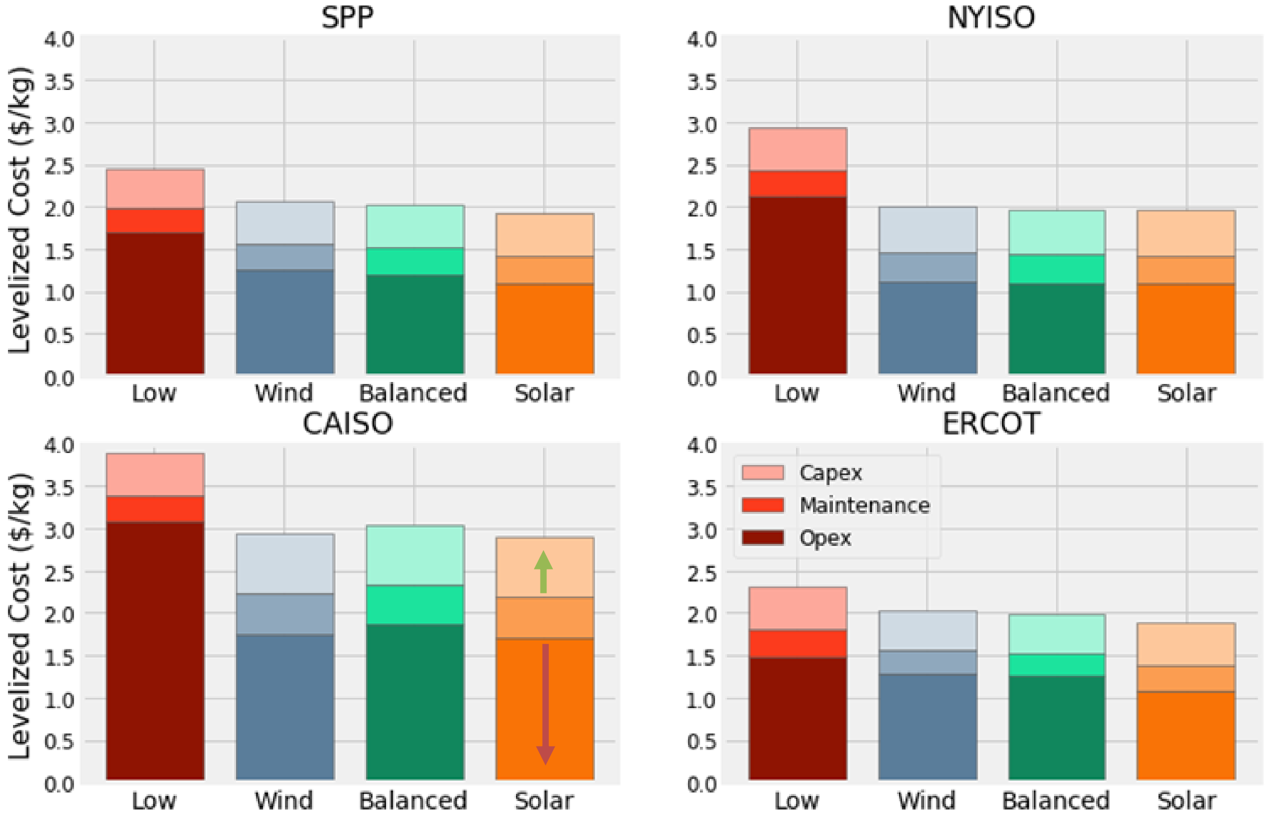
- Validated and improved estimates of threshold price / market size combinations for each application



Case Study 1:
Power-to-H2

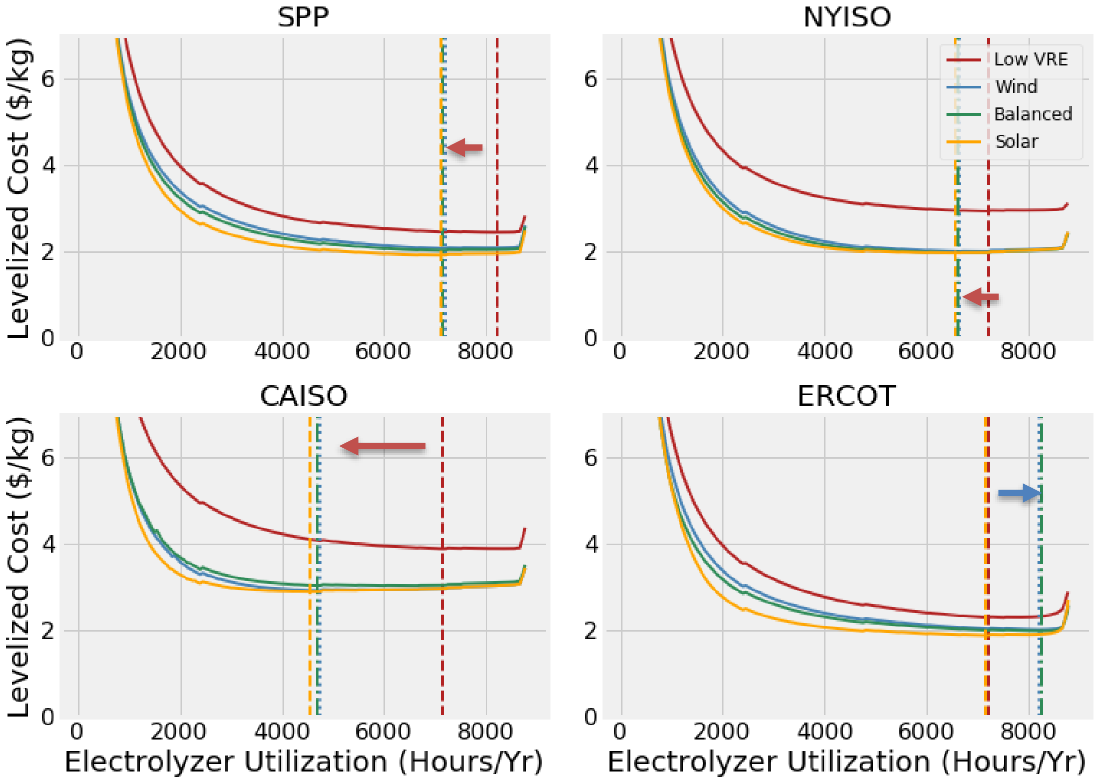
High VRE futures can lower H2 production costs

- **Low-priced electricity in high VRE scenarios can reduce dominant operating costs**, leading to total cost reductions of 15-30%.
- NYISO/CAISO include carbon costs



- **Optimal capital utilization rates may decrease by up to 30% in high VRE scenarios** (except ERCOT **wind**).

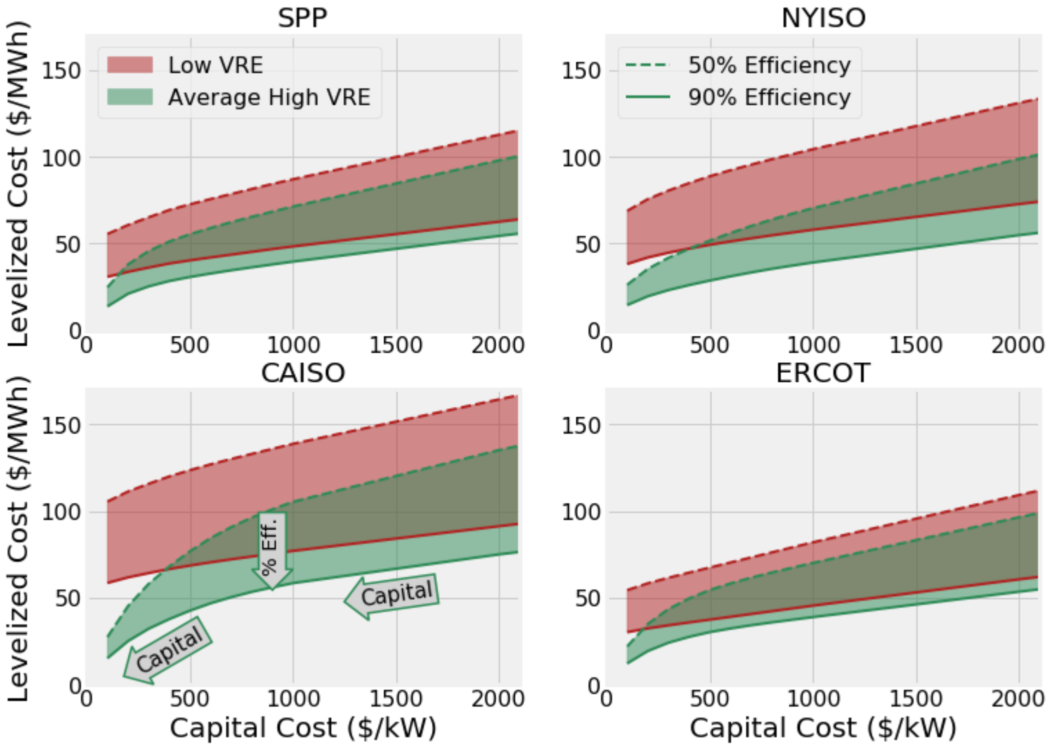
→ larger opportunity for Capex reductions (e.g. CAISO **solar**).



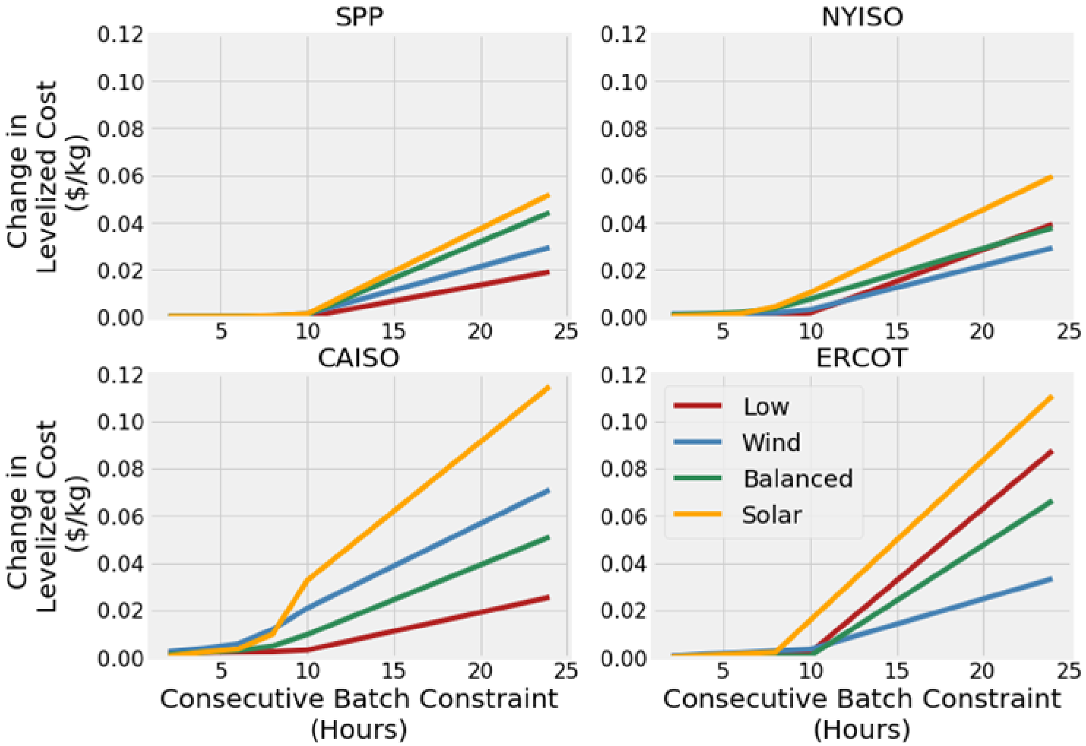
Case Study 1:
Power-to-H2

High VRE may shift R&D focus for electro-products from process efficiency improvements to Capex reductions

- ◆ Abstracting to generic electro-product.
- ◆ Capital cost intensive industries see lower VRE-price effect → less sensitive
- ◆ Band of efficiency opportunities generally narrower in high VRE futures as average prices decline, R&D focus may shift towards capex reductions.



- ◆ Alkaline electrolysis is a very flexible process with quick start-up and shut-down times
- ◆ Other electro-products may require longer batch-processing. Sensitivity analysis shows stronger increase in levelized costs in high VRE futures with longer run-times due to increased price volatility.



Case Study 2:
District Energy System

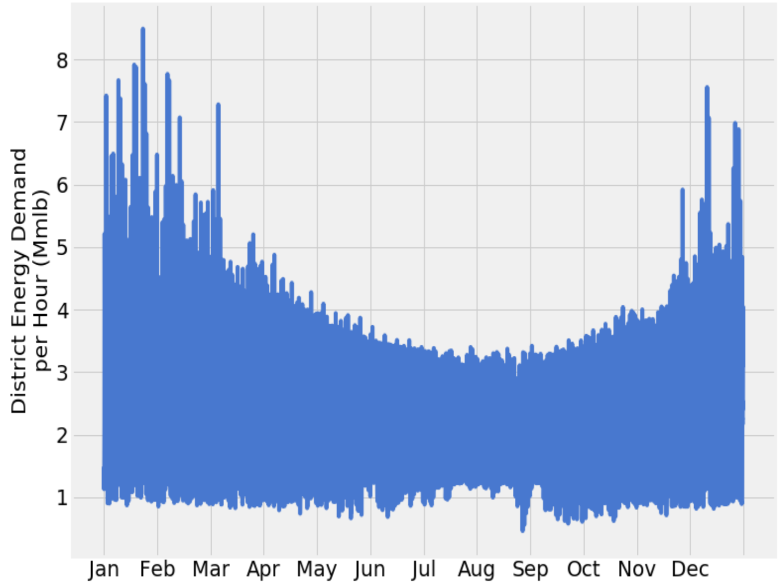
Adding Heat Pumps to District Energy Systems to Increase Flexibility

- Background:
  - Most District Energy Systems (DES) rely on fossil fuels as main energy source for district heating (and occasionally cooling), sometimes in the form of combined-heat-and-power. Transfer medium is steam or water. Up to 5800 DES 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.
- Assumptions:
  - 3 scenarios:

    1) No heat-pump | 2) Hybrid (20% supplementary HP) | 3) All-electric HP

  - Capex: Natural gas boilers: $120/kW, cogeneration $800/kW, heat pump $800/kW

Steam demand profile for Manhattan



Case Study: world's largest DES (by ConEd in Manhattan, 1700+ large customers)

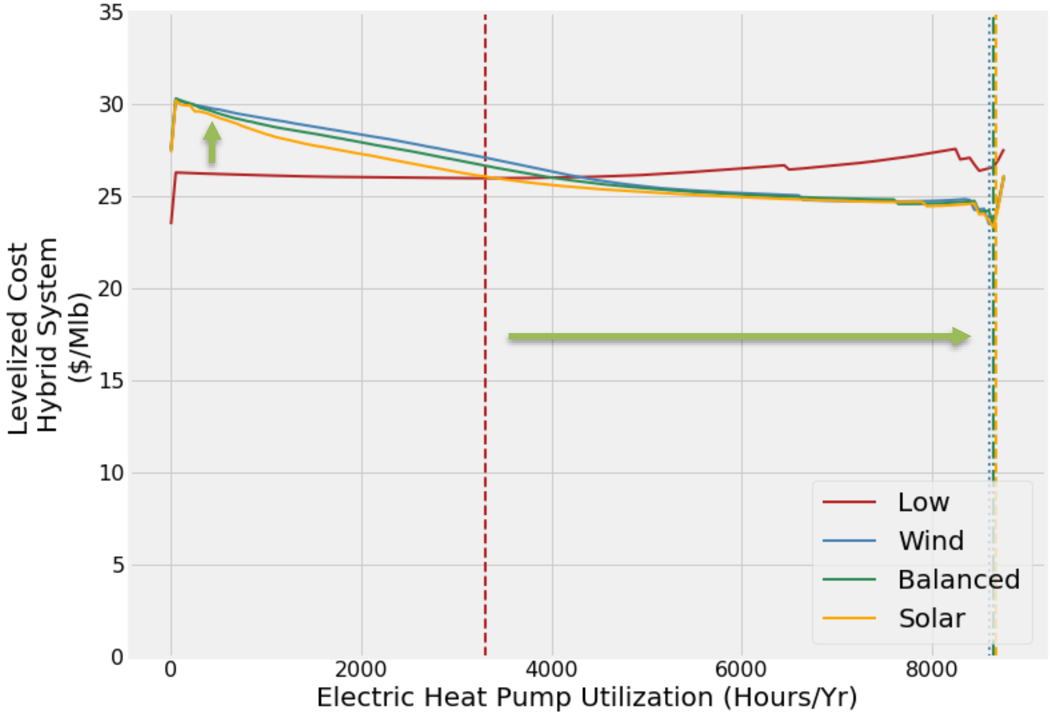
- winter-peaking system with maximum demand of 8MMlb steam/h, 15% reserve margin
- Legacy system: 60% natural gas boilers, 40% cogeneration (exposure to electricity revenue Δ)
- Fixed distribution cost for 100 miles ($32MM)
- Monthly varying natural gas costs $4.6-6/MMbtu (inclusive of carbon price)
- Heat pump *Coefficient of Performance:* 3

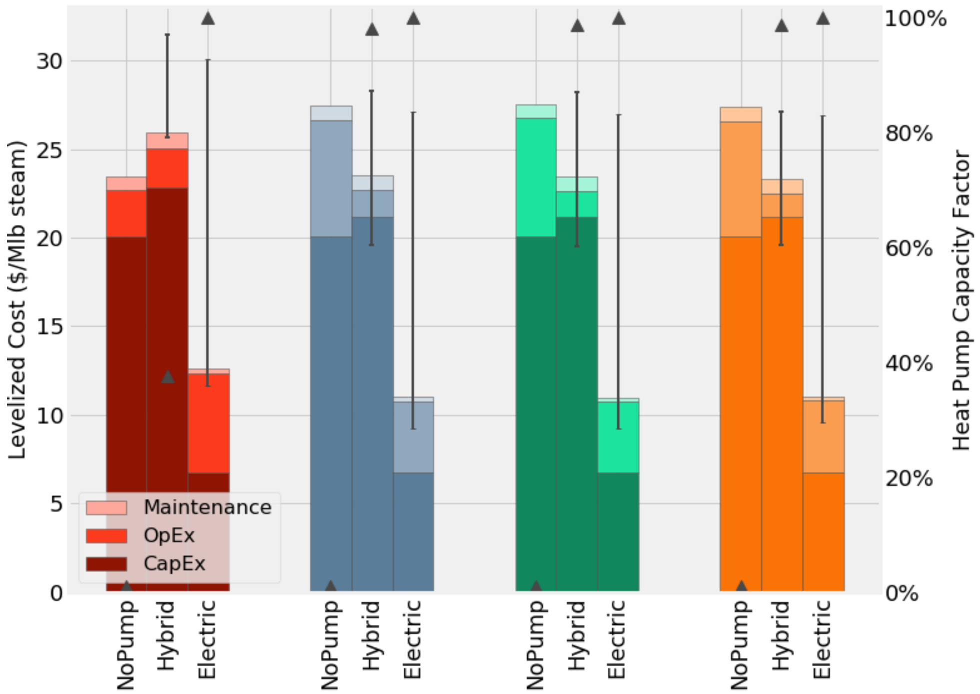
Case Study 2:
District Energy System

Flexibility Option Lowers Costs only in High VRE future

- Hybrid System: Unit costs rise at low heat pump utilization in high VRE futures because lower electricity prices decrease cogeneration revenue
- **Low VRE**: Cost-optimal to have minimal heat pump use
- **High VRE**: Cost-optimal to use heat pump all but the most expensive hours

- In high VRE future Opex rise for no heat pump scenario
- Only in high VRE scenarios hybrid system decreases levelized costs (-$5 vs +$3/Mlb steam)
- All-electric heat pump case seems to be most cost-effective choice in all scenarios (assuming one can forego fossil capital costs and retire the cogeneration facility)





Energy Technologies Area

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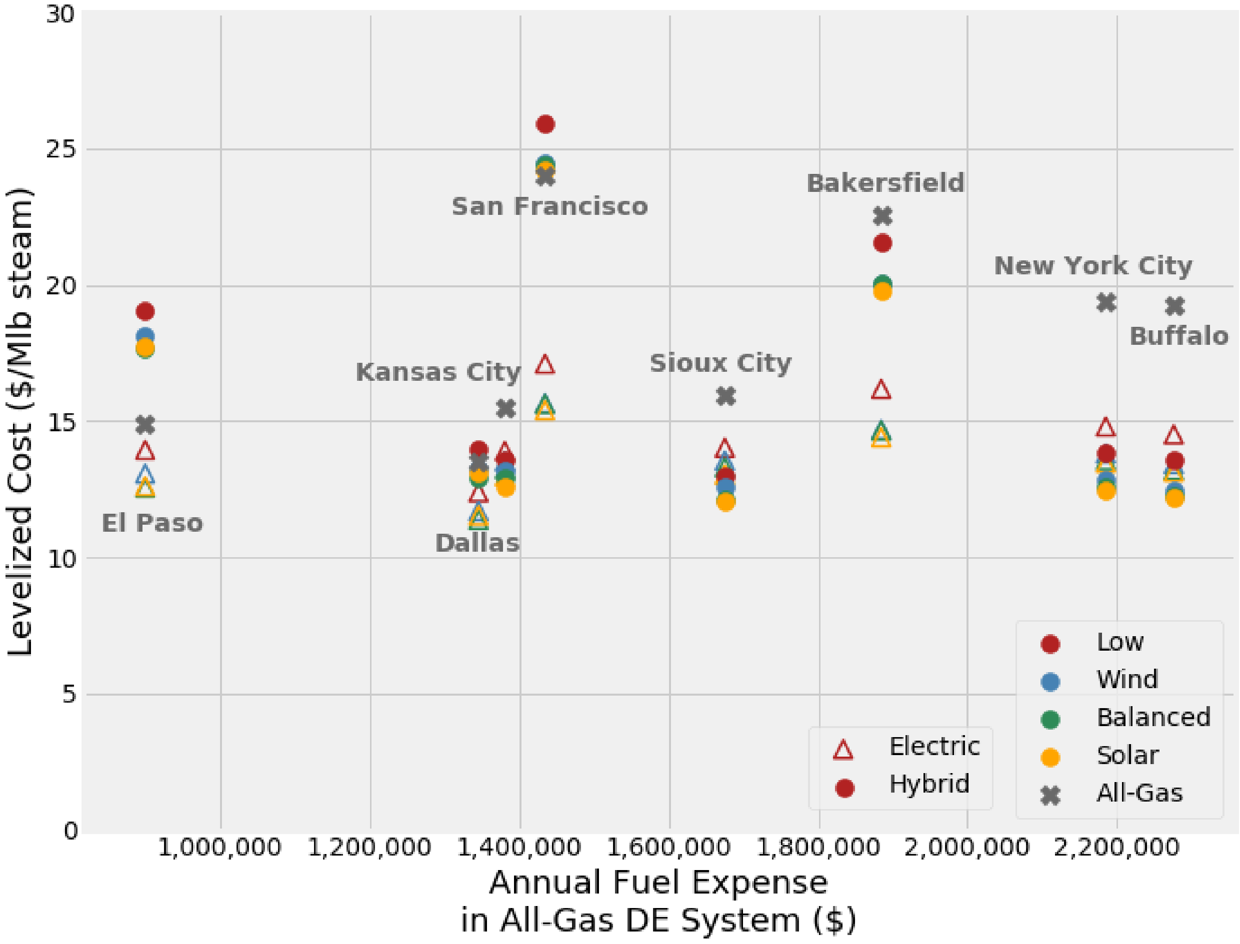
Case Study 2:
District Energy System

District Energy Systems without Cogeneration and with Low Gas Expenses more Resistant to Change

Stylized college campuses' DES around the U.S.

- 2 locations per ISO → different load shapes
- Hourly load shapes based on *Build America Simulation* for school + apartment buildings – load factor lower than for ConEd
- Heat pump *Coefficient of Performance:* 5
- **No cogeneration**
- Varying natural gas costs by month and region (carbon fee in CA and NY)



- Hybrid systems perform worse in locations with low annual natural gas expenses (<$1.5MM), 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:
Desalination

Adding Storage to Desalination Systems to Increase Operational Flexibility

◆ Background:

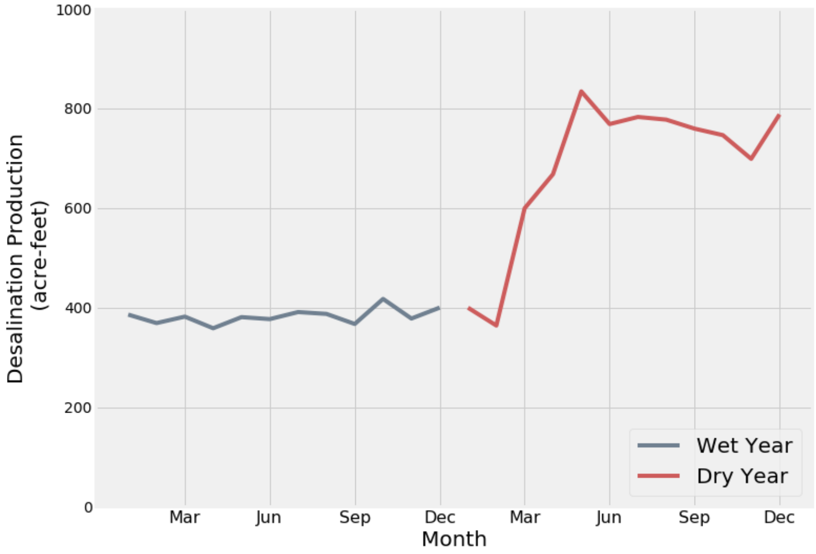
- ❑ Water desalination with reverse osmosis is an energy-intensive process, employed throughout the U.S., not just for ocean water but also brackish ground water
- ❑ With increased storage reservoirs, water desalination plants can increase production during hours with low electricity prices and dispatch 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
- ◆ Storage costs for water (building water reservoirs @ $1000/acre-foot) is low relative to many other electro-commodities

Desalination water demand in El Paso



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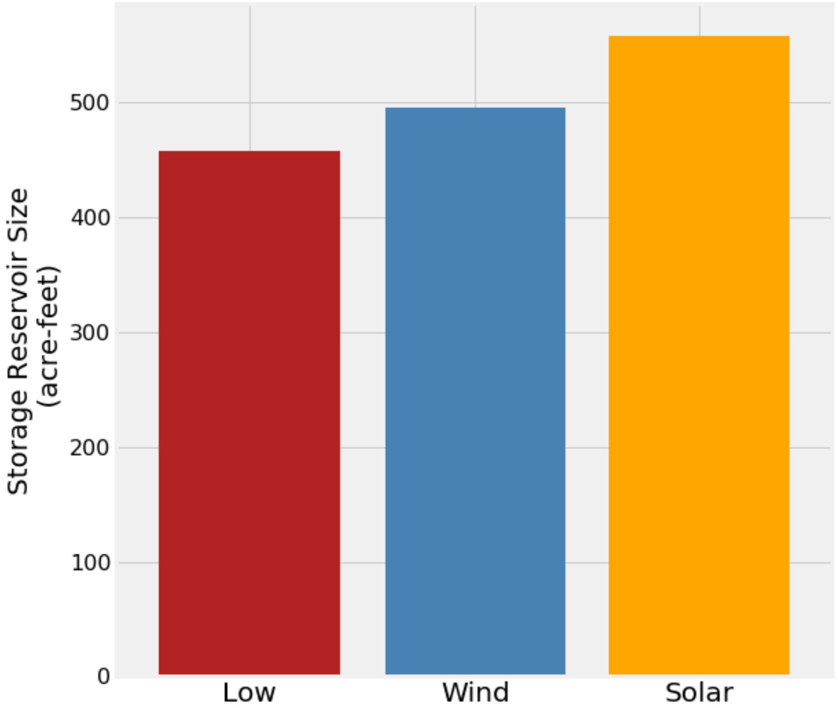
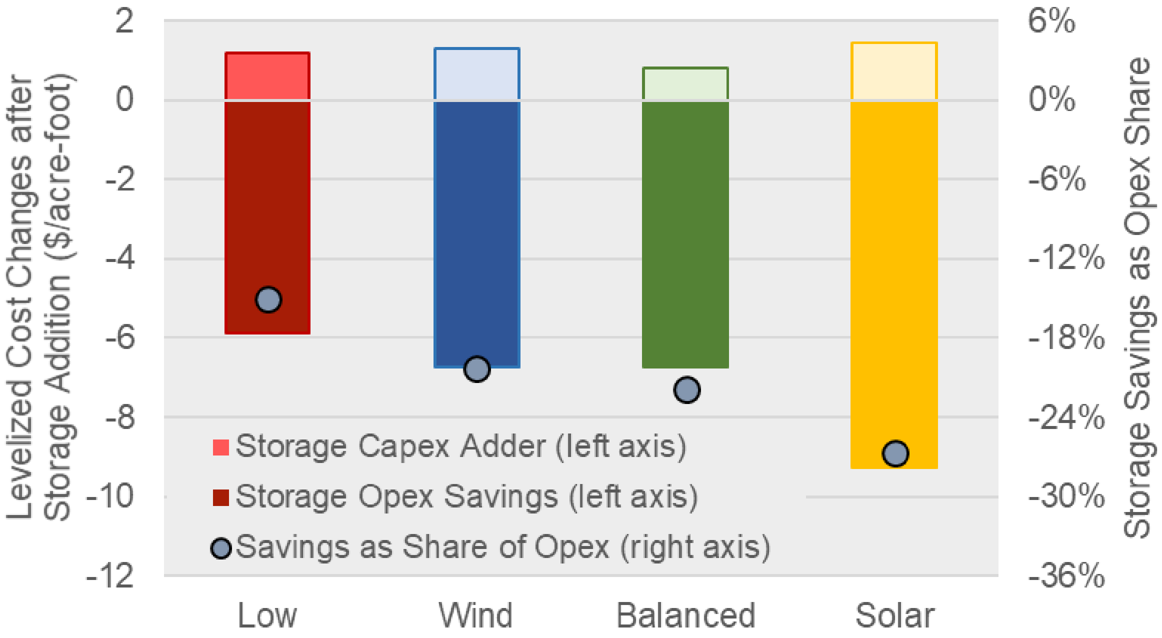
Case Study 3:
Desalination

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

- Storage additions are cost-effective in all scenarios
- Optimal storage **size** and storage **utilization hours** increase in high wind and high solar scenarios (+11% and +27% of hours)
- Overall unit costs of delivered water decrease modestly in high VRE future as desalination Capex is dominant
- Focusing only on marginal expenses, storage addition offers higher savings in high VRE scenarios (up to 27% Opex reduction in **solar** scenario)





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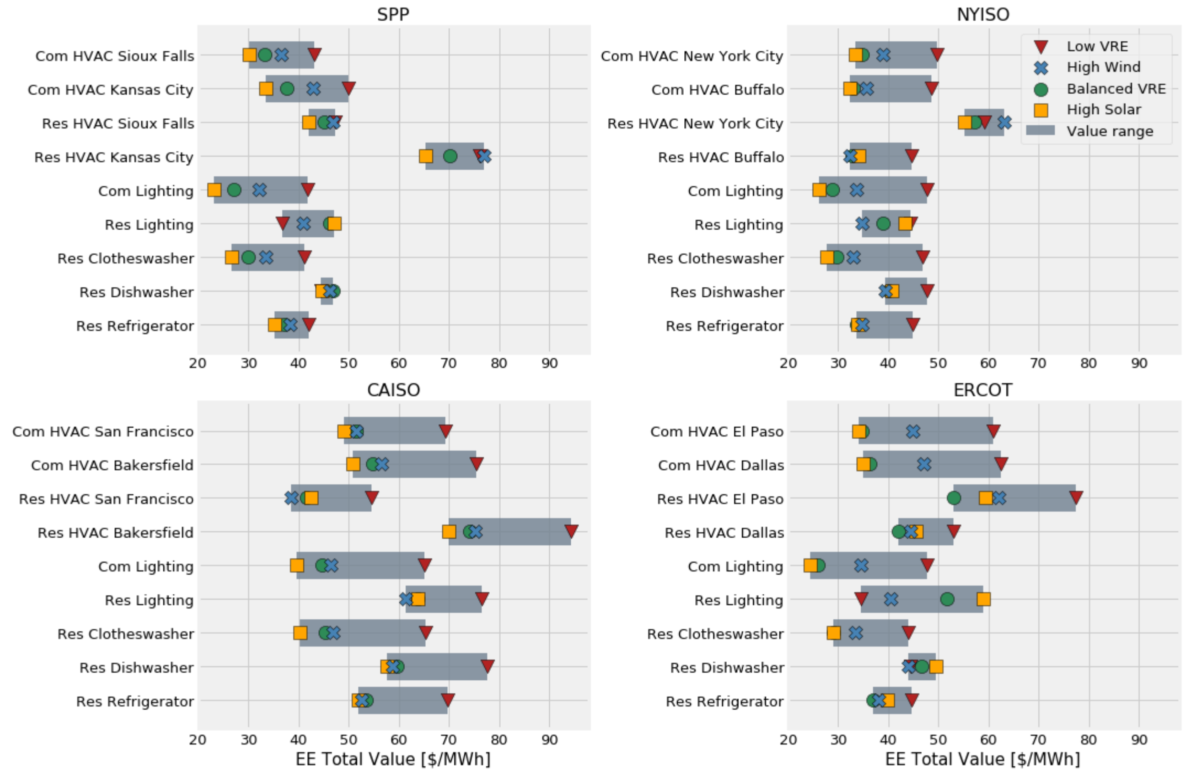
Other Demand-Side Impacts:

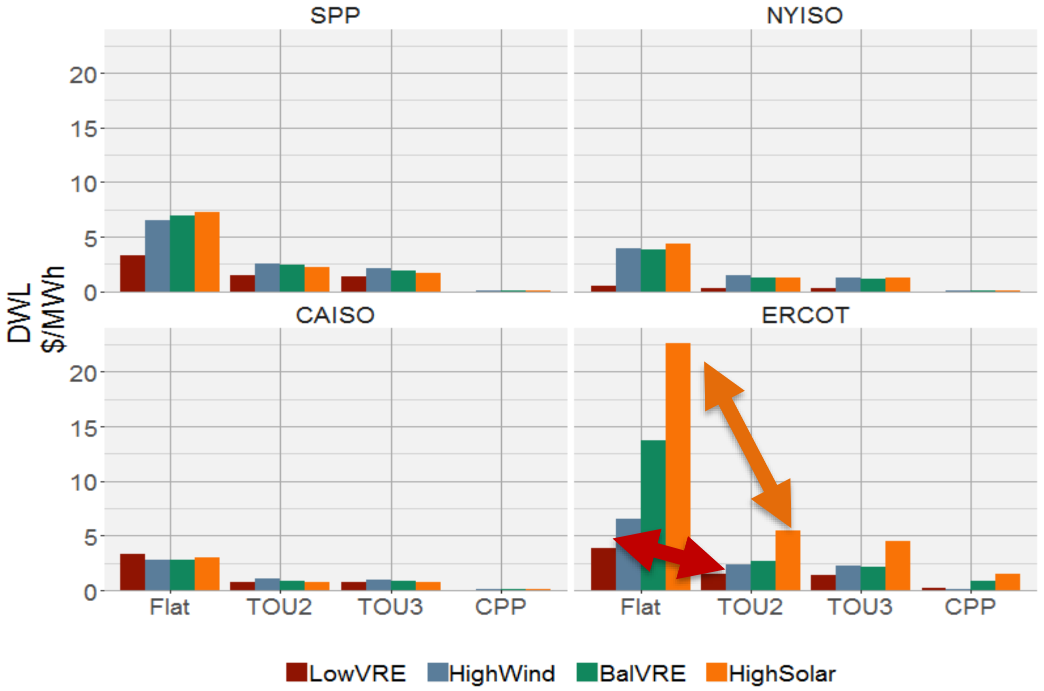
Energy Efficiency

- Value of energy efficiency measures decreases in high VRE scenarios, particularly for midday savings (commercial HVAC and lighting).
- Targeted evening savings become more valuable, especially in high solar futures (residential lighting, dishwashers). Opportunity for added DR capabilities.



Rate Design

- Increasing level of time-differentiation makes retail rates more efficient economically.
- However, rates that are optimized for a low VRE scenario may lead to higher losses in a high VRE future than simple flat rates.
- Adopting more sophisticated rates becomes more important in high VRE futures.



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Thank you for your attention!

For questions and feedback:

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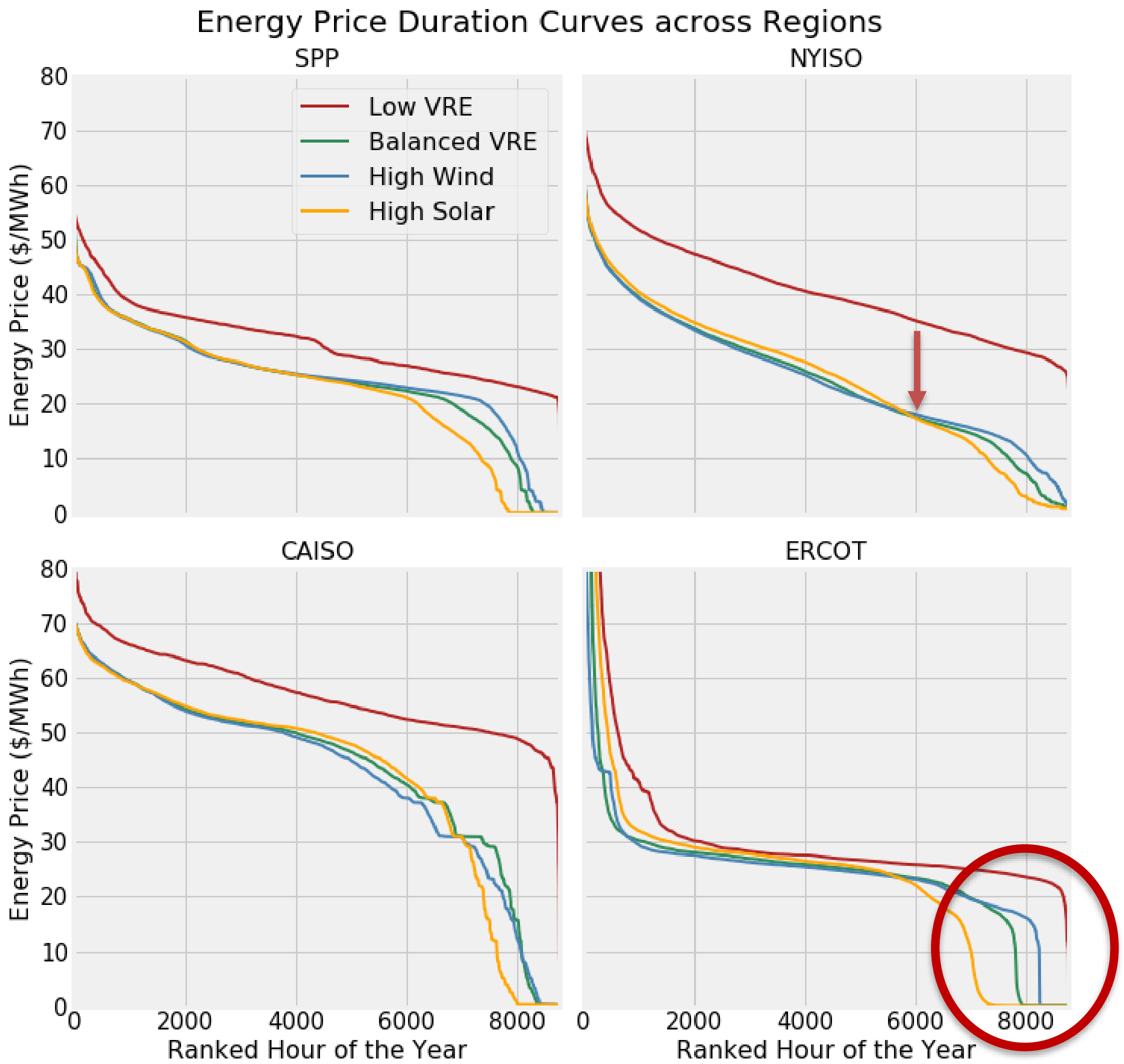
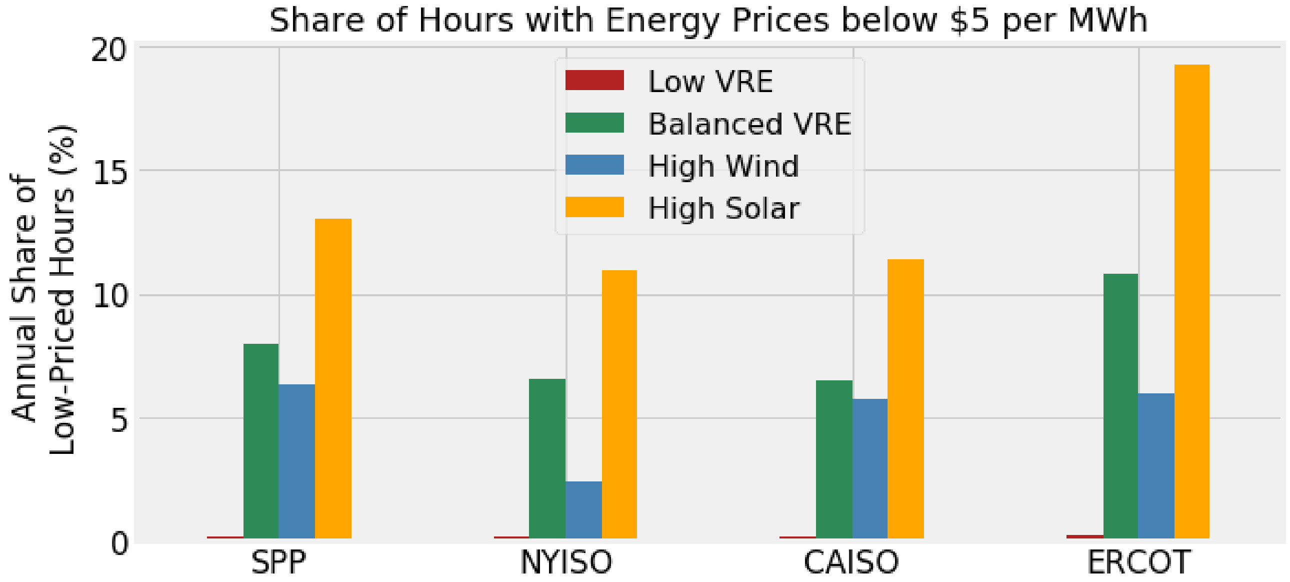
Low Energy Prices Become More Frequent Under High VRE Scenarios

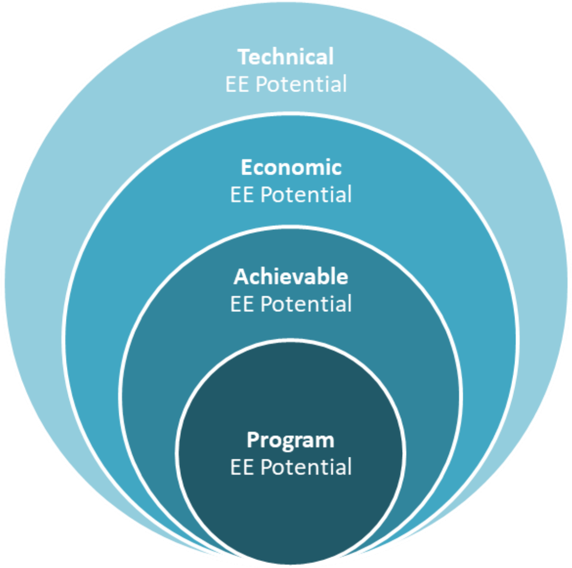




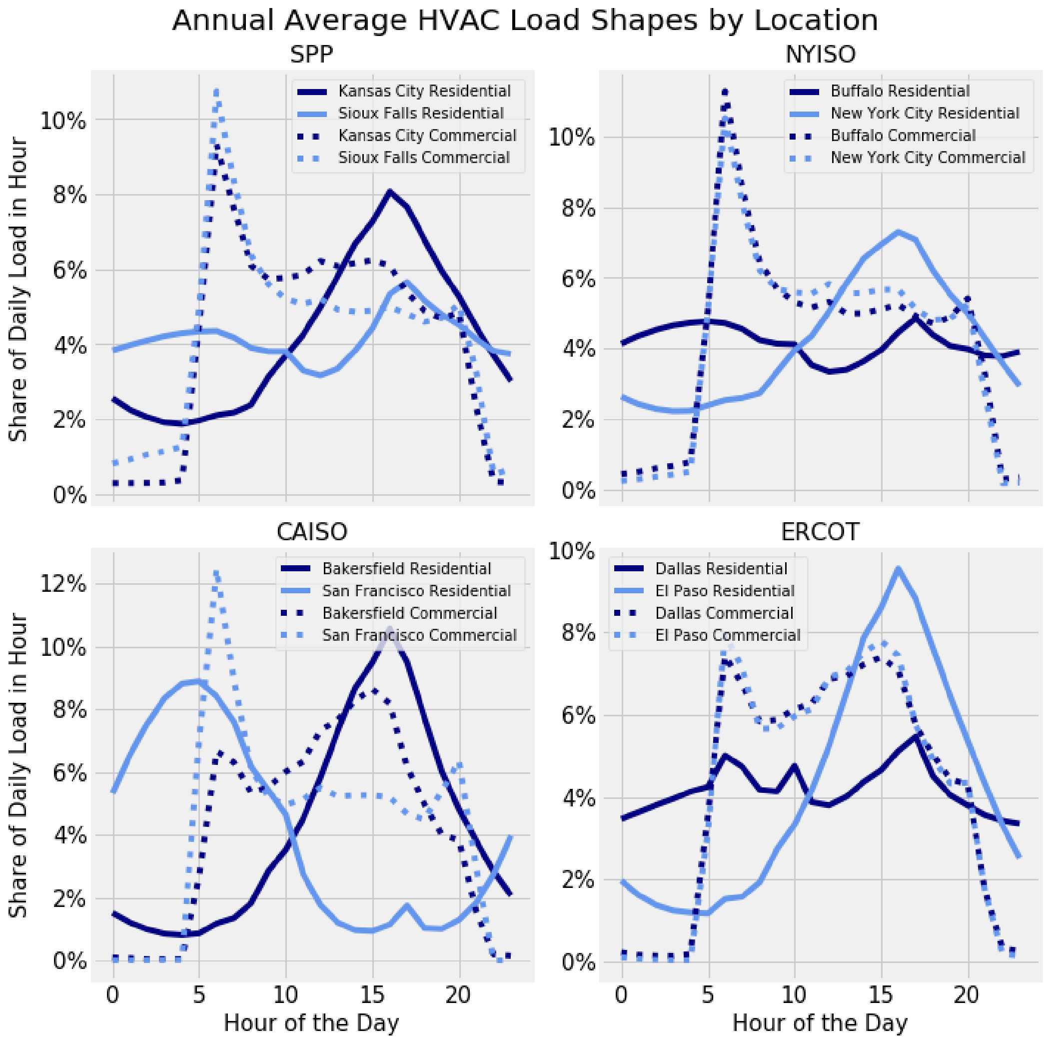
- In some regions, the shape of the price distribution curve does not change dramatically but is merely shifted downwards (e.g. NYISO)
- Other regions feature a more pronounced ‘cliff’, featuring a dramatic increase in hours with very low prices (e.g. ERCOT)
- Low prices driven by **solar** more than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

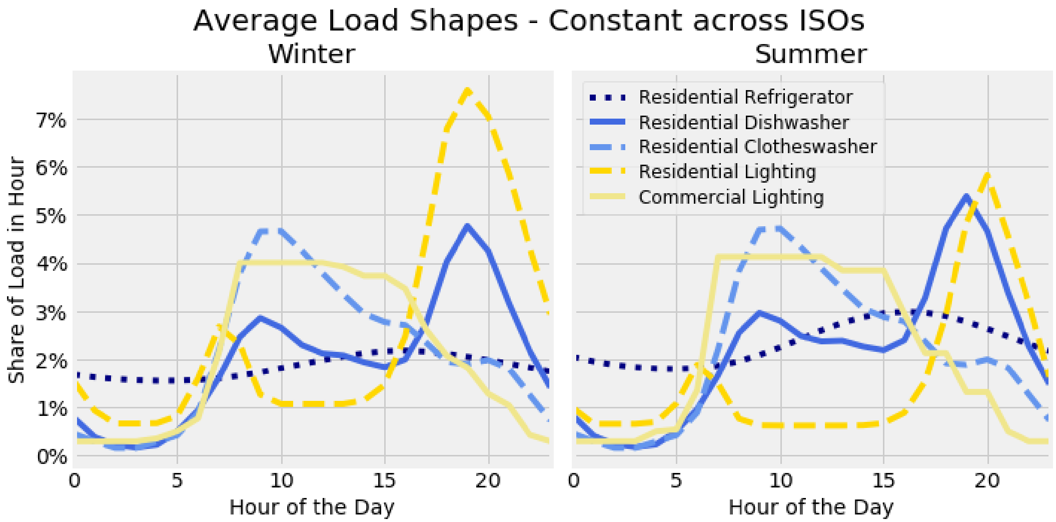
VRE Impacts on Energy Efficiency– Overview of Issue

- Central task for utility administrator is the **selection of suitable combinations of EE measures that decrease overall energy consumption, curb demand growth and reduce overall electric system needs in the most cost-effective manner.**
- Cost-effective EE measure selection depends significantly on the other available energy supply resources, as they determine the value of energy efficiency. With changing energy supply options and changing peak and off-peak periods the best EE portfolio will likely change.
- Given the longevity of EE measures it is important to consider future changes upfront.
- Recent Trends:
  - ❑ Total Resource Cost Test most widely used throughout the US, considering EE primarily as a system-level resource (locational net-benefits analyses in some states)
  - ❑ **Time-dependent Valuations** leverage higher resolution time series (AMI):
    - average/seasonal coincidence factors → hourly capacity and energy values
  - ❑ **Integrated forward-looking assessments** use dynamic calculation of avoided costs, full life-time of EE contributions:
    - Use scenario analyses (including high VRE cases) in monte carlo simulations / IRPs (NWPCC, PacifiCorp, Californian mandates)



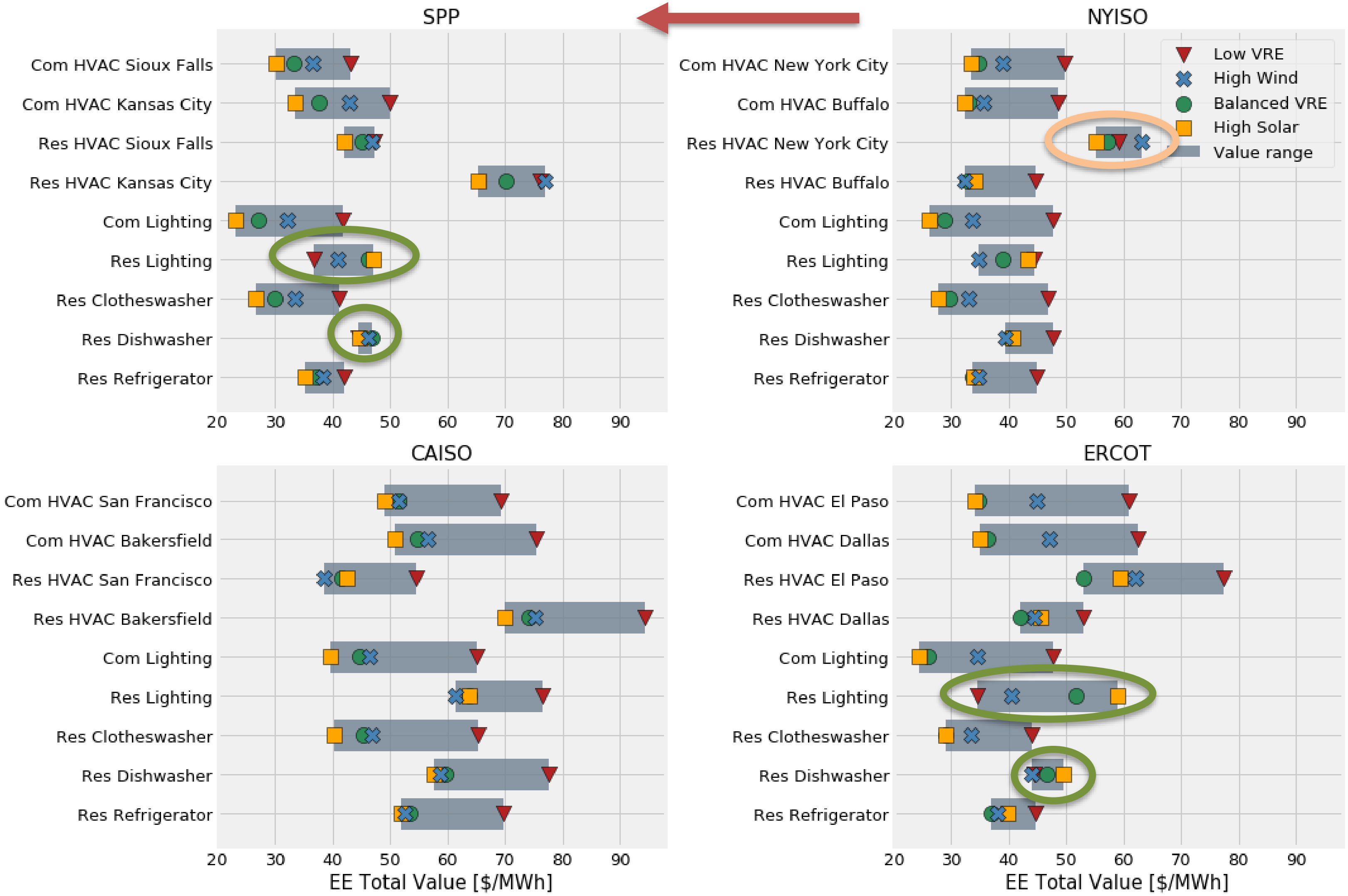
Data Sources for EE modeling





- Limited data available for empirical EE savings shapes that have high time and geographic resolution. Instead of saving shapes we use load shapes whose profile is assumed to be congruent with EE savings.
- Location-dependent:
  - HVAC load shapes: Building America Simulation that have 8760h resolution and reflect climate differences based on TMY3 data
- Location-independent:
  - Residential and commercial lighting shapes based on “Build America Simulations” (load magnitude varies but not shape)
  - Appliances based on California Database for Energy Efficient Resources (2011) with 8760h resolution for PG&E territory

EE value decreases for most measures, driven by strong decline in energy value



◆ As average energy prices decrease between low (▼) and high VRE scenarios, the EE **energy value decreases** in all regions for all measures ($5-$20/MWh), *except for residential lighting in ERCOT driven by rare price spikes*

◆ Average capacity prices increase in most high VRE scenarios (except in CA).

- In SPP and NYISO EE capacity value increases can counteract some energy value declines.
- In CAISO and ERCOT capacity value reductions lead to additional value loss.

◆ **Total 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 lightening and dishwashers **increase** in value

◆ Opportunity for DR value add

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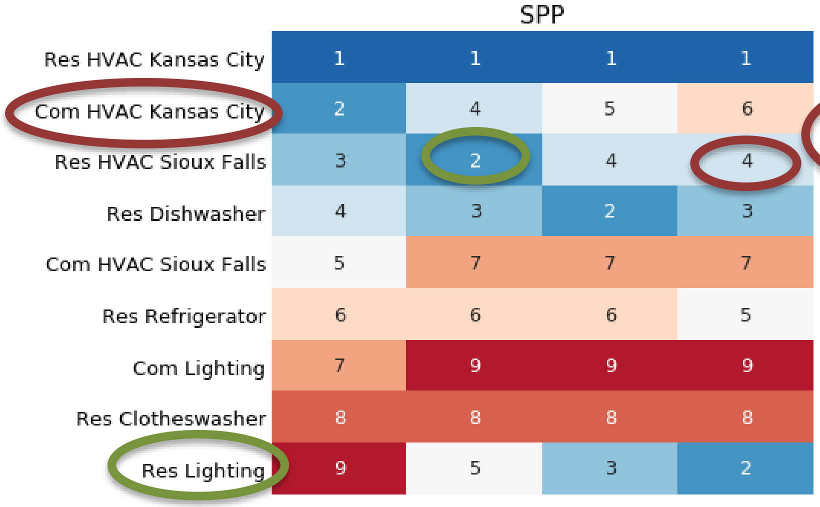
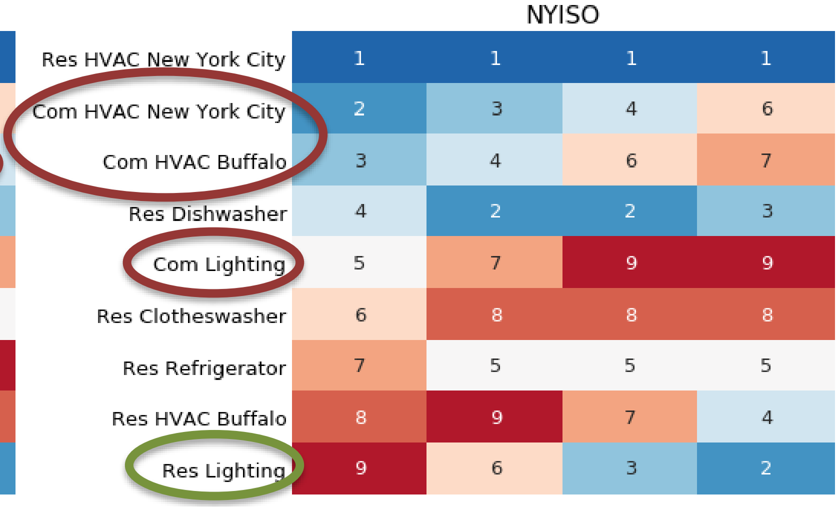
Relative Value Ranking of some EE Measures changes, especially in high solar scenarios



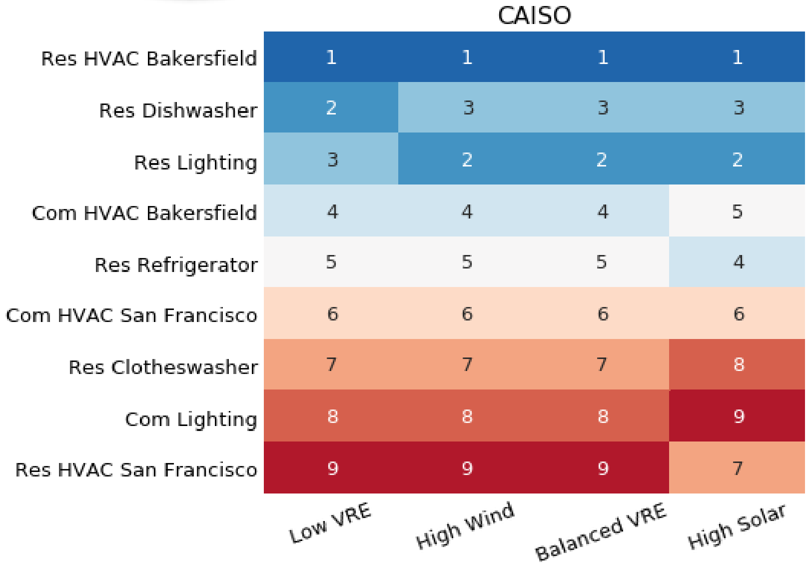
SPP

	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



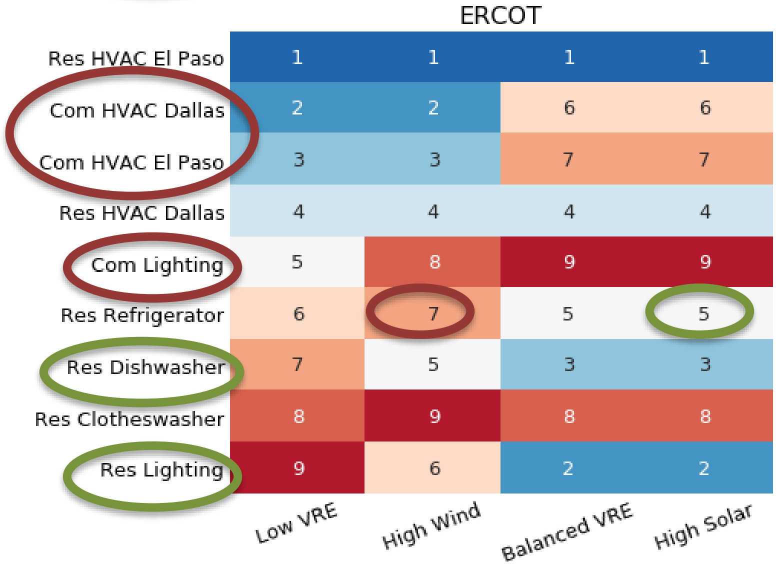
NYISO

	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 base scenario
- 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

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

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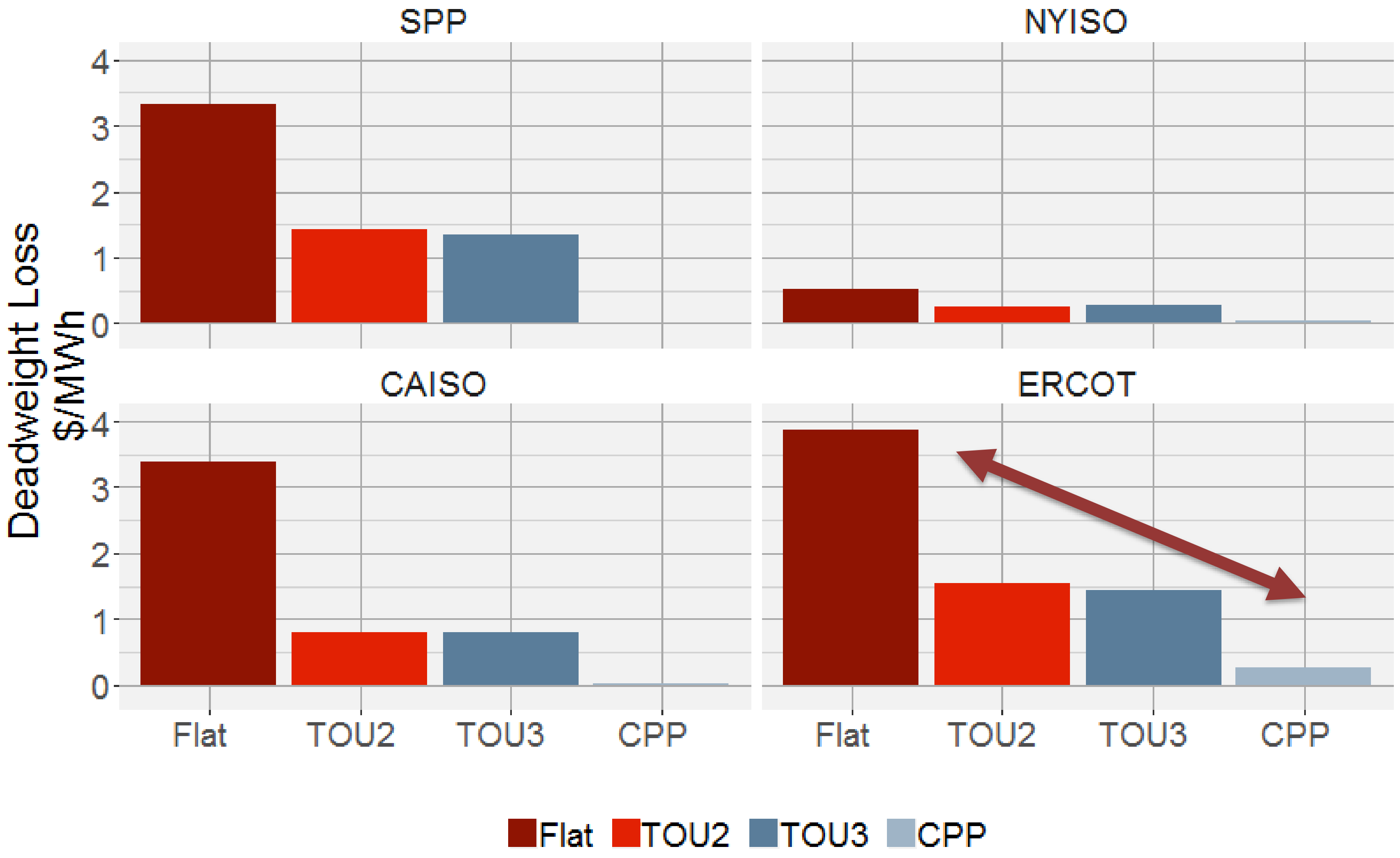
VRE Impacts on Rate Design – Overview of Issue

- Key questions
  - Under different high VRE future scenarios, how might retail rates further diverge from marginal cost?
  - What new aspects should retail rate designers consider when drafting the next generation of rates?
- Method: **minimize deadweight loss (DWL)**
  - Design rates that minimize DWL in a low VRE future
  - Project low VRE rates on high VRE futures and calculate DWL
  - Redesign rates to minimize rates in high VRE futures

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

Time-Differentiated Rates Are More Efficient Than Flat Rates



- DWL decreases with closer approximation of 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

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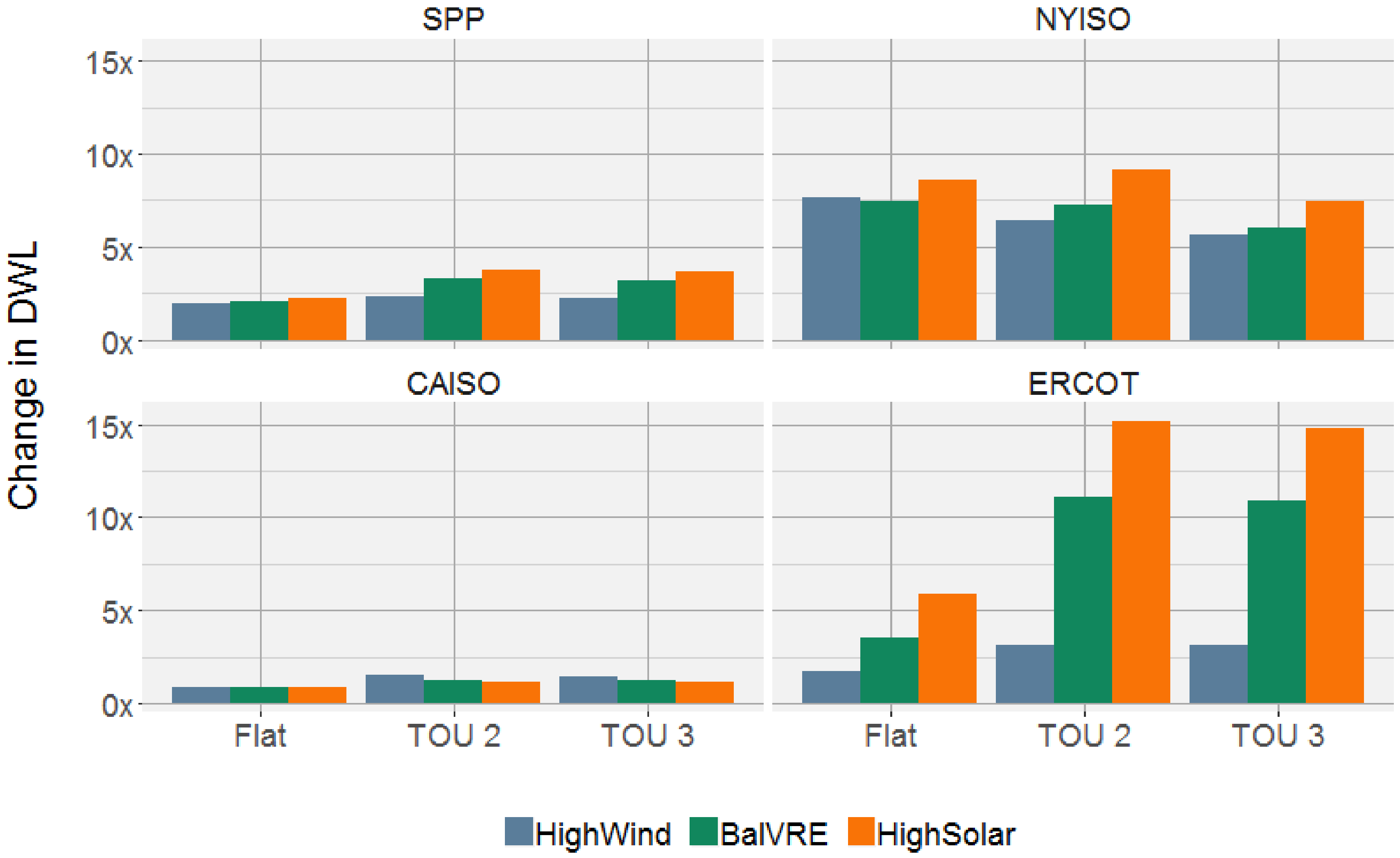
LowVRE Rates in HighVRE Futures:

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

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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 offer the most improvements to economic efficiency
- ERCOT benefits greatly from time-varying rates in general

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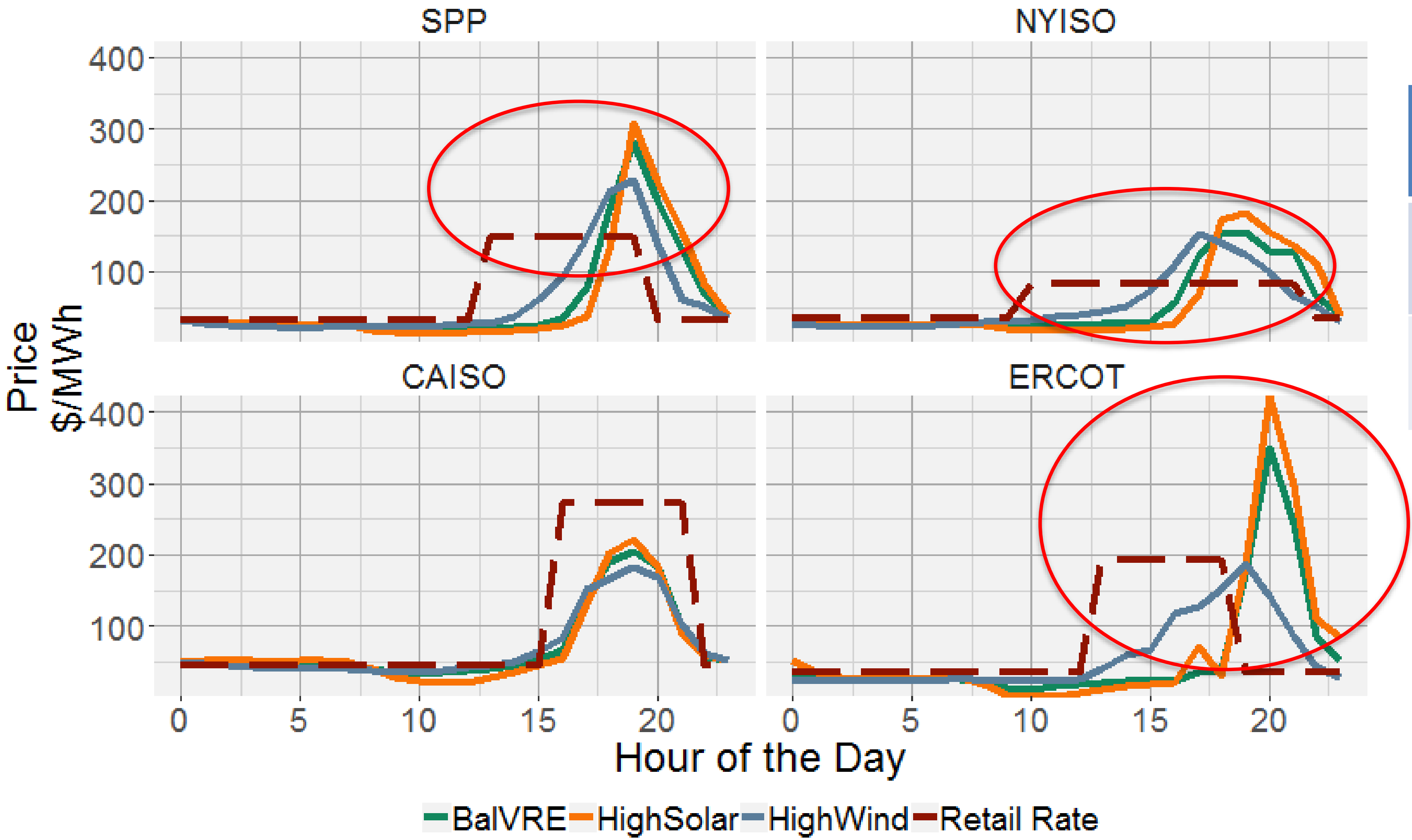
2-Period TOU:

Mistiming of Peak Period in HighVRE



Rate Characteristics	
Rate Structure	2-Period TOU
Season	Summer

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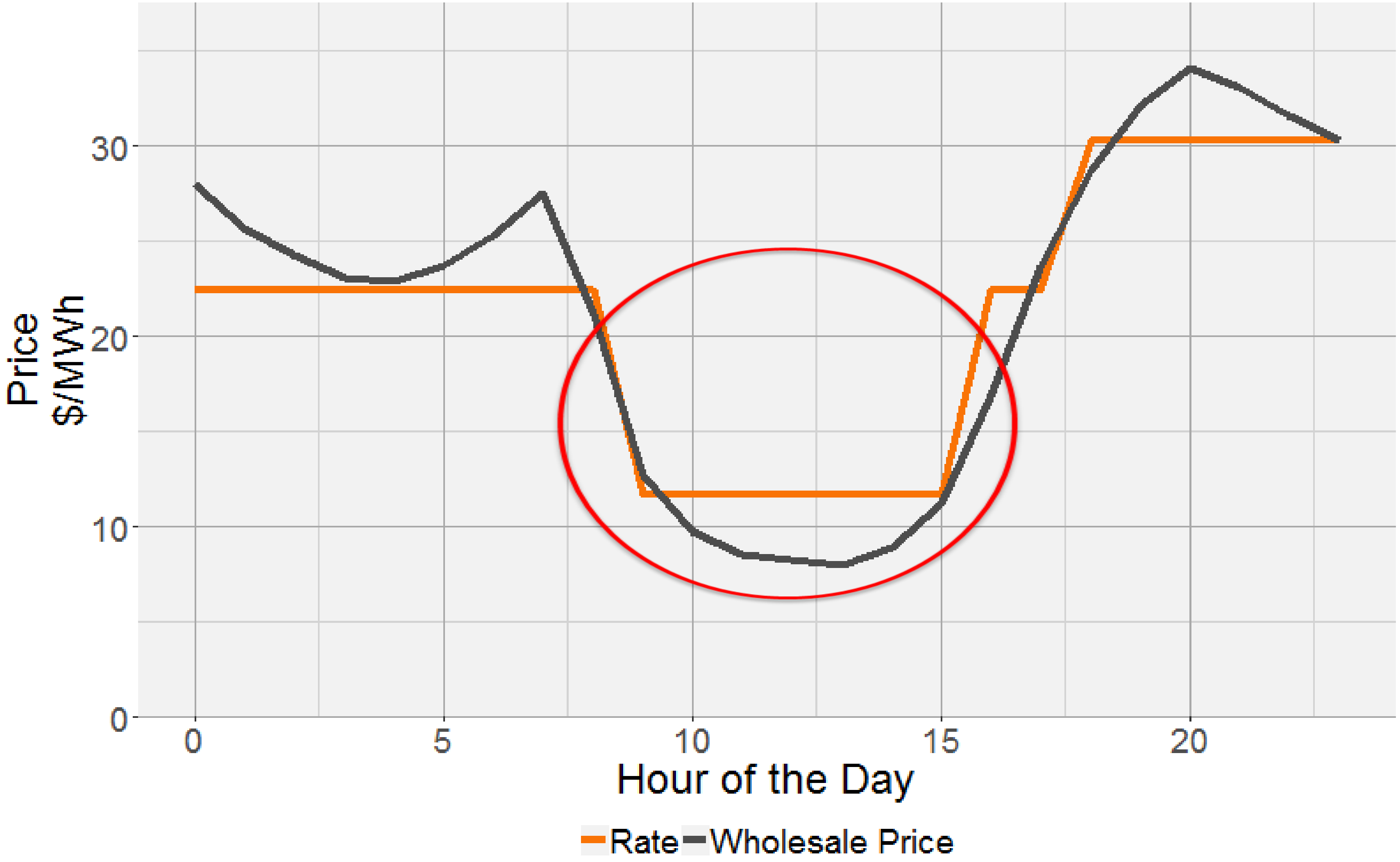
3-Period TOU:

Super-Off Peak is Efficient in HighSolar Future



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

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