Impacts of High Variable Renewable Energy (VRE) Futures on Wholesale Electricity Prices, and on Electric-Sector Decision Making

Joachim Seel, Andrew Mills, Ryan Wiser

Lawrence Berkeley National Laboratory

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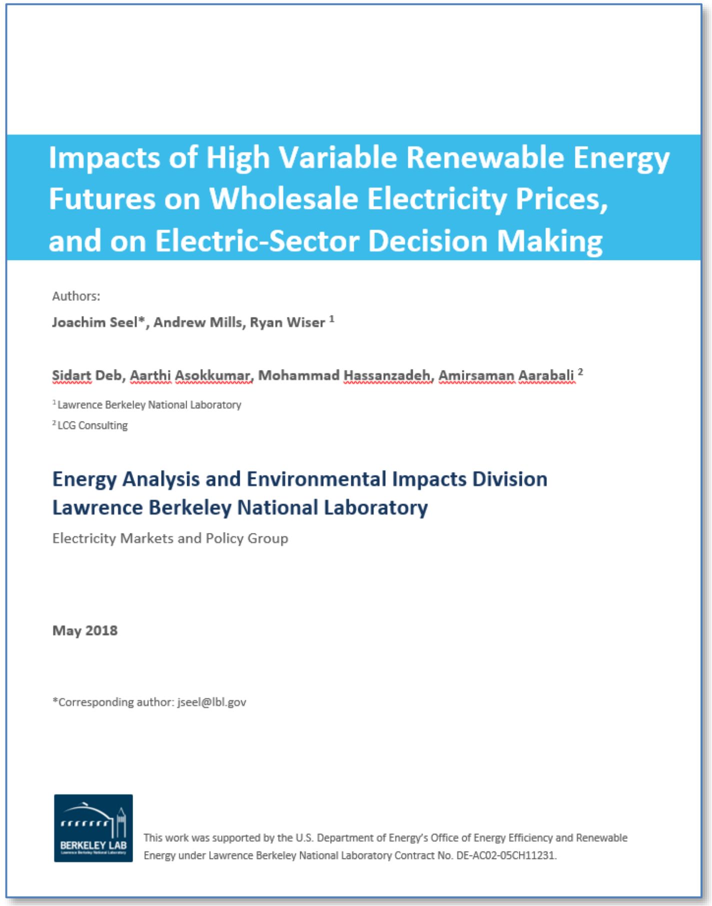
A full technical report and underlying data sets are available at:

https://emp.lbl.gov/publications/impacts-high-variable-renewable



Impacts of High Variable Renewable Energy Futures on Wholesale Electricity Prices, and on Electric-Sector Decision Making

Authors:

Joachim Seel*, Andrew Mills, Ryan Wiser [1]

Sidart Deb, Aarthi Asokkumar, Mohammad Hassanzadeh, Amirsaman Aarabali [2]

[1] Lawrence Berkeley National Laboratory

[2] LCG Consulting

Energy Analysis and Environmental Impacts Division
Lawrence Berkeley National Laboratory

Electricity Markets and Policy Group

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*Corresponding author: jseel@lbl.gov

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Executive Summary

Increasing penetrations of variable renewable energy (VRE) can affect wholesale electricity price patterns and make them meaningfully different from past, traditional price patterns. Many long-lasting decisions for supply- and demand-side electricity infrastructure and programs are based on historical observations or assume a business-as-usual future with low shares of VRE.

Our motivating question is **whether certain electric-sector decisions that are made based on assumptions reflecting low VRE levels will still achieve their intended objective in a high VRE future.** We qualitatively describe how various decisions may change with higher shares of VRE and outline an analytical framework for quantitatively evaluating the impacts of VRE on long-lasting decisions.

We then present results from detailed electricity market simulations with capacity expansion and unit commitment models for multiple regions of the U.S. for low and high VRE futures. We find a general decrease in average annual hourly wholesale energy prices with more VRE penetration, increased price volatility and frequency of very low-priced hours, and changing diurnal price patterns. Ancillary service prices rise substantially and peak net-load hours with high capacity value are shifted increasingly into the evening, particularly for high solar futures.

While we only highlight qualitatively the possible impact of these altered price patterns on other demand- and supply-side electric sector decisions in this publication, the core set of electricity market prices derived here provides a foundation for later planned quantitative evaluations of these decisions in low and high VRE futures.

Wholesale Price Effects of 40-50% Wind & Solar

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

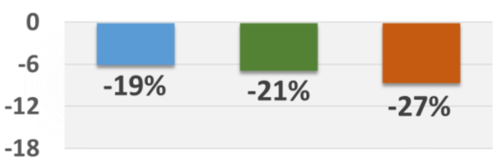
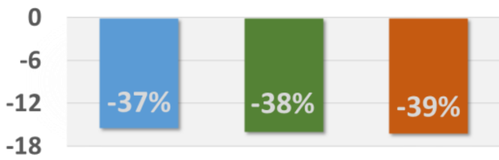
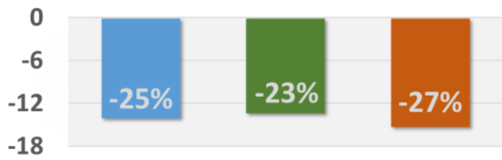
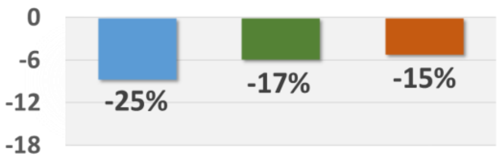
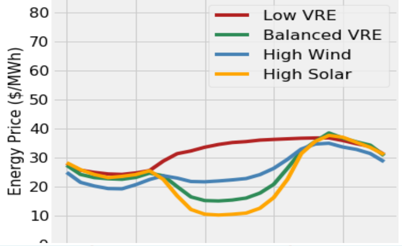
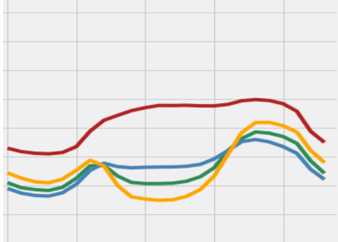
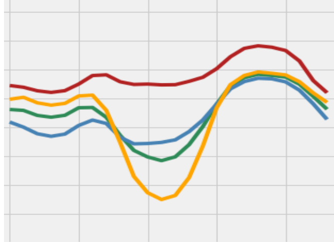
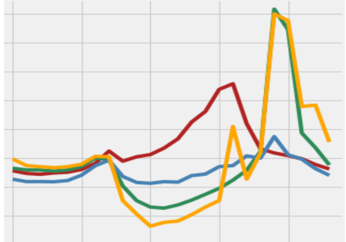
Impacts in 2030 relative to baseline with 2016 wind & solar shares	**Southwest Power Pool** 2016: 18% wind & 0% solar			**NYISO (New York)** 2016: 3% wind & 1% solar			**CAISO (California)** 2016: 7% wind & 14% solar			**ERCOT (Texas)** 2016: 16% wind & 1% solar		
	Wind	Balanced	Solar	Wind	Balanced	Solar	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		

Table of Contents

Overview of Briefing

- Background: Evidence of VRE-induced Price Changes and Theory
- Research Motivation and Objective: Examples of Electric-Sector Decision Making
- Analytical Framework for Quantitative Assessment
- Key Findings: Changes at High VRE Penetrations
- Discussion and Outlook

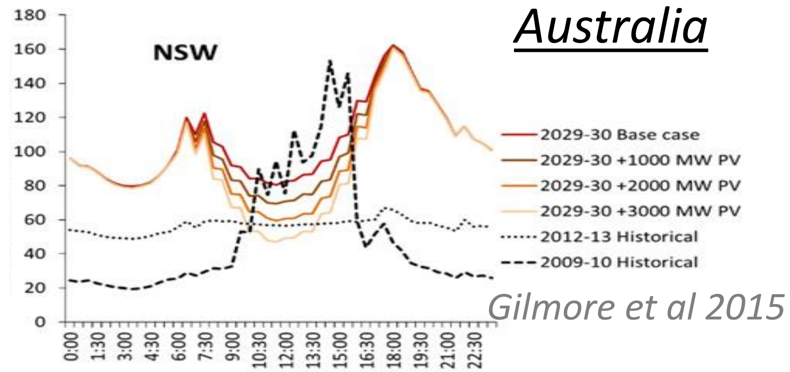
Introduction: VRE Characteristics and Their Expected Impacts

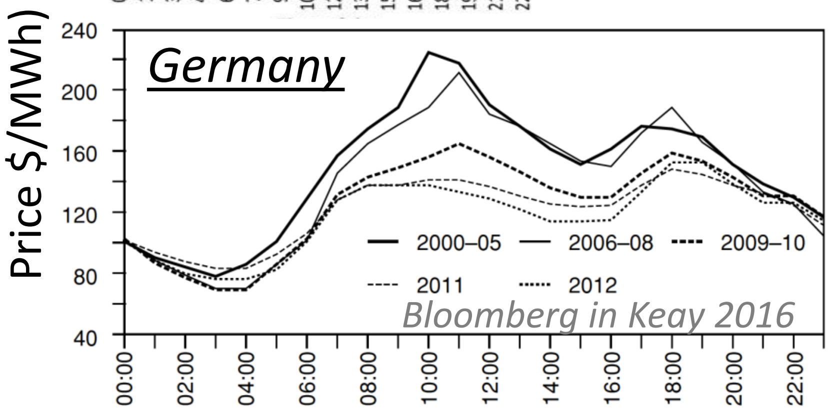
- Extensive global and U.S. literature demonstrates general tendencies as VRE increases
- Impacts affected by the underlying physical & institutional flexibility of the electric system
- Some of the impacts highlighted to right will be less pronounced when the rest of the electricity system is more flexible
- Policies incentives for VRE at times magnify effects

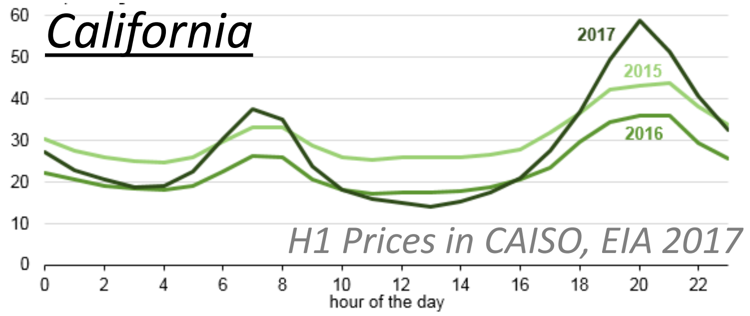
Characteristics of VRE
- Output variability
- Output uncertainty
- Location dependence
- Low marginal cost

Physical Impacts of VRE
- Increased total capacity
- Increased reserves / AS / ramping need
- Reduced operations of baseload units
- Favor low capital-cost technologies
- Favor flexible supply / demand / storage
- Benefit of increased transmission

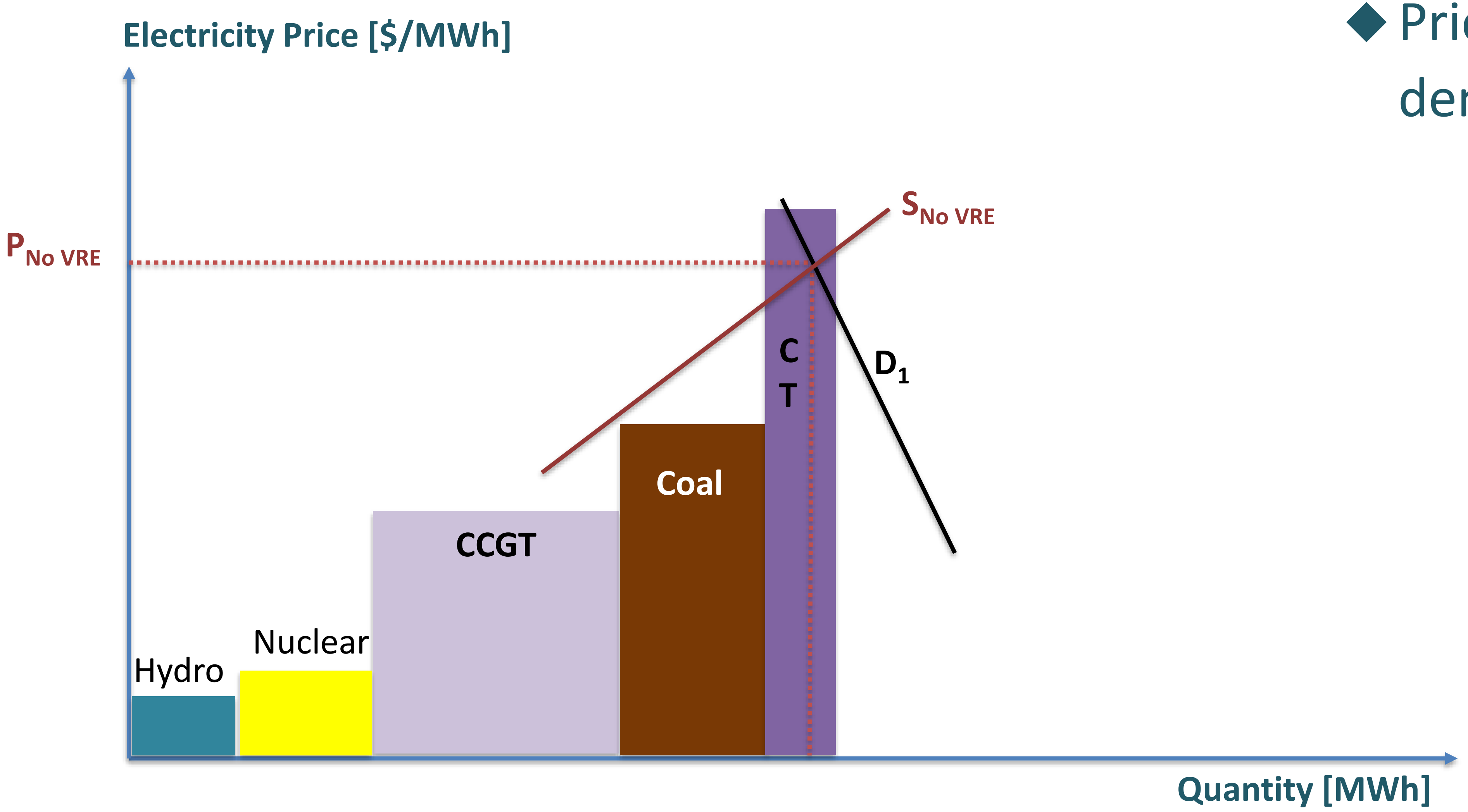
Wholesale Price Impacts of VRE
- Altered temporal patterns of prices
- Greater price volatility, more negative prices
- Altered geographic patterns of prices
- Suppressed average prices, in short term
- Price suppression eases somewhat as capacity equilibrates
- Greater revenue from AS, capacity, scarcity events





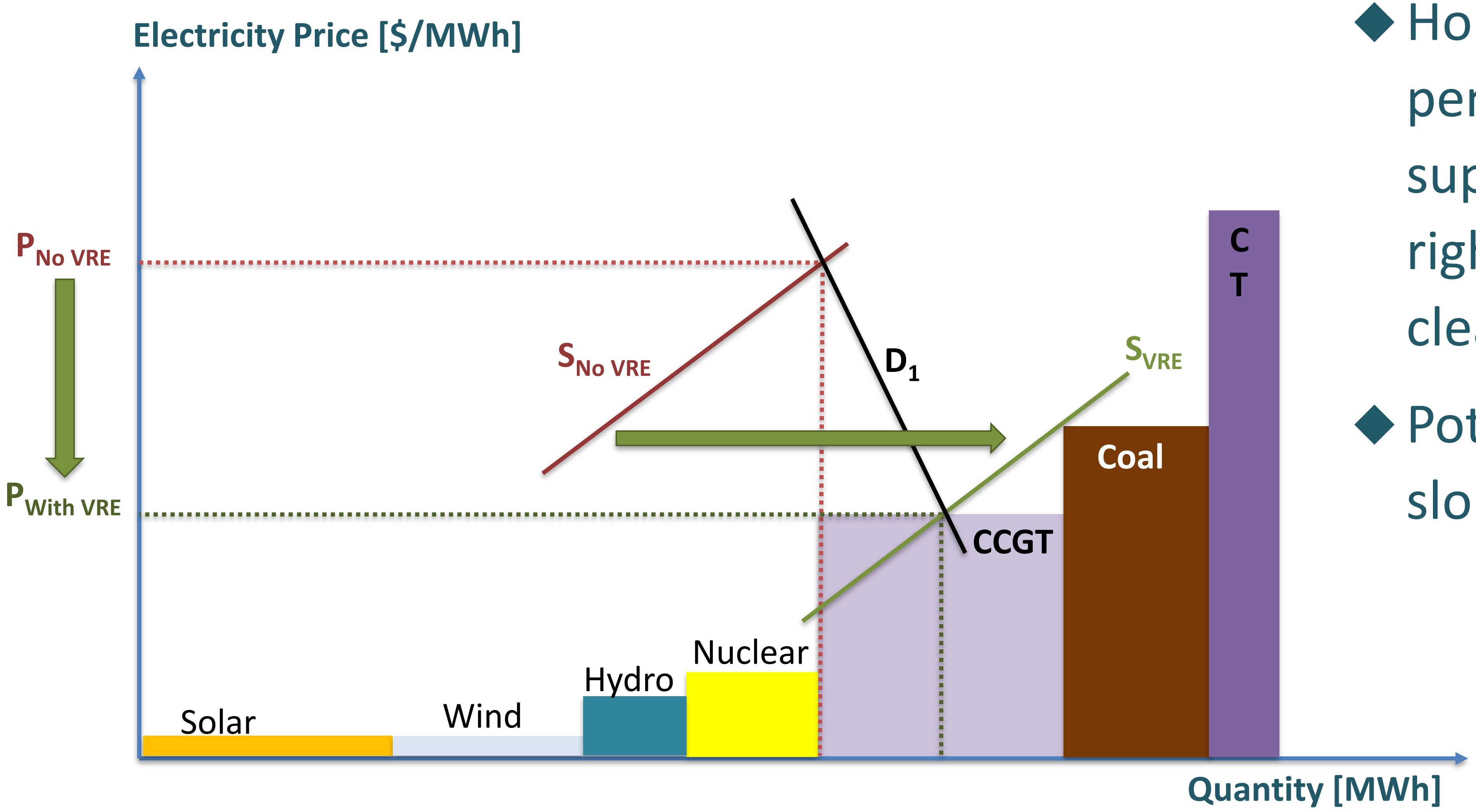


Theoretical Background
Price Formation with VRE



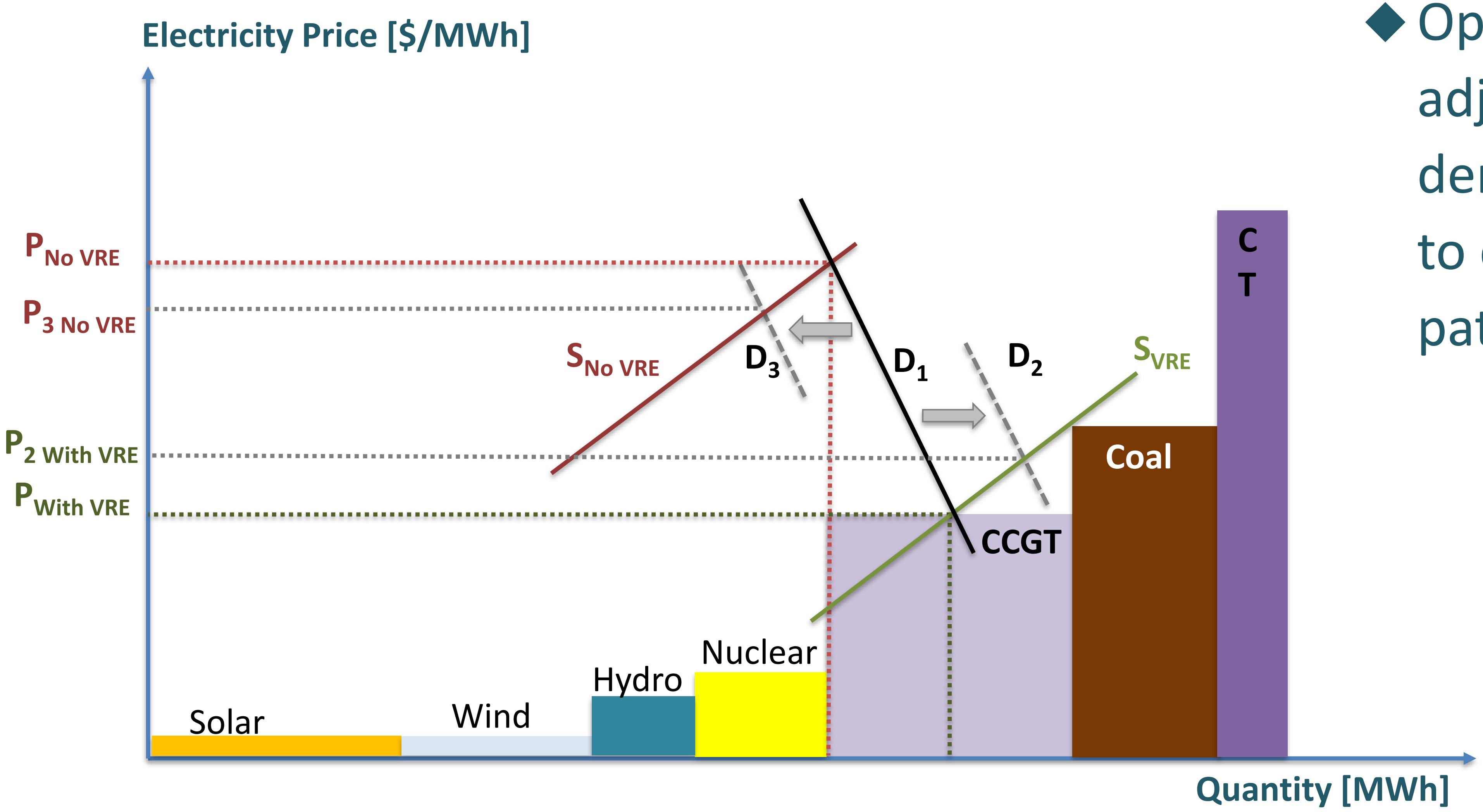
- Price set by variable demand levels

Theoretical Background
Price Formation with VRE



- Hours with high VRE penetration shift supply curve to the right and lower clearing prices
- Potential supply slope change

Theoretical Background
Price Formation with VRE



- Opportunity to adjust longer-term demand in response to changed price patterns

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Research Objective

Will electric-sector decisions based on past assumptions still achieve their intended objective in high VRE futures given impacts of VRE on wholesale power markets?

Demand-Side Decisions	Supply-Side Decisions
Choice of Energy Efficiency Portfolios	Incentives for Nuclear Revenue Sufficiency, Flexibility Retrofits
Electrification of Gas End-Uses: Which water heater is better?	Investing in Combined Cycle Gas Turbines or Reciprocating Engines
Location Choices of EV Charging Infrastructure	Cost-Effectiveness of Energy Storage and Capability Selection
Advanced Commodity Production Processes	Hydropower Relicensing under Alternate Water Flow Regimes
Demand Response Service Design	
Retail Rate Design	

Impacts on VRE Assets

- Shifts in location to areas that are better aligned with high-priced hours
- Change in project design to maximize value instead of energy production
  - solar: higher ILR, SW orientation
  - wind: larger rotors, taller towers
  - VRE + storage
- Change in investments decisions between wind and solar
- Change in operations and contractual structures, allocation of pricing risks

Focus of briefing is on possible impacts on wholesale electricity prices

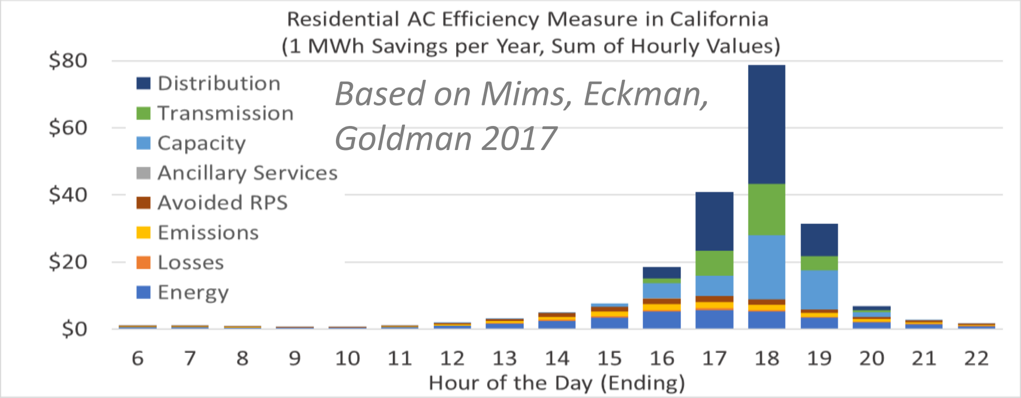
See **briefing appendix** for more detailed description of decisions

Example: Energy Efficiency Portfolios

- Decision Type
  - Approve EE portfolios to decrease energy consumption, curb demand growth, reduce electric system needs in most cost-effective manner
- Decision Analysis
  - National Standard Practice Manual suggests forward-looking, long-run marginal costs to evaluate EE cost-effectiveness
  - Wide variety of cost-effectiveness evaluation practices. Nascent move to time-dependent valuation instead of average prices, opportunity to incorporate forward-looking scenario analysis

Traditional Design

- Demand peak reductions via Energy Star Residential Air Conditioners that emphasis late afternoon savings



High VRE Future

- Lower share of near-constant load reduction measures (refrigerators)
- Net-Demand peak reductions that focus on evening savings via residential lighting efficiency measures or street lighting measures

Example: Electrification of Gas End-Uses: Water Heaters

Electrification of gas end-uses promises environmental and system-level benefits via load management

Deployment barriers are often economic and influenced by a large variety of policies, programs and regulations

- Decision Type
  - Adapt policies, programs and regulations (e.g. California's building code Title 24) to evaluate **electric vs. gas-fired water heaters** for new/substantially retrofitted buildings
- Decision Analysis
  - Time-dependent-valuation of gas and electricity consumption over 30 years, potentially via scenario-analysis
  - Broad range of value stream inclusion (energy, capacity, emissions, transmission, losses, RPS)

Traditional Design

- Preference for gas-fired water heaters
- No coupling to electric market dynamics

High VRE Future

- Preference for electric water heaters
- Strategic use of load to participate in demand-response programs

Example: Nuclear Flexibility Incentives

- Decision Type
  - Increase R&D on flexible nuclear demand design and operations
  - Address technical regulations on nuclear plant operations
  - Provide financial incentives to keep nuclear plants operating

- Decision Analysis
  - Compare revenue options of traditionally operating and "flexible" nuclear plants

Traditional Design	High VRE Future
Baseload nuclear plant with near constant power output and annual capacity factor near 100%	Nuclear plant operations with significant hours of non-maximum power output
Little ramping capabilities and no participation in ancillary service markets	Regular ramping within limits, potentially only seasonal operation
No special financial incentives to support O&M costs	

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Research Design for Assessment of Wholesale Market Outcomes in 2030

SPP | NYISO | 4 Regions | CAISO | ERCOT

Low VRE in 2030	High VRE in 2030
• **Low VRE** future with wind and solar shares frozen at 2016 levels	• **Balanced VRE** (20% Wind, 20% Solar) • **High Wind** (30% Wind and at least 10% Solar) • **High Solar** (30% Solar and at least 10% Wind)

LCG Consulting Models

- **Capacity expansion model (Gen-X)** to establish non-VRE 2030 generator portfolio (conventional options) based on social cost minimization
- **Market simulation model (UPLAN)** co-optimizes hourly energy and ancillary service prices; extract capacity prices and CO_2 emissions
  - Emission costs drive clearing prices → exogenous projections of permit prices by planning entities ($52/t CO2 in CAISO, $24/t in NYISO)
  - Load levels determine demand for existing and new generators→ load forecasts by planning entities
  - Fuel prices affect generator investment choices and merit order dispatch → forecasts based on geographically adjusted EIA data

- Market designs assumed to be roughly similar to those in place today in each region
- Limit leakage by assuming high VRE levels in neighboring markets; limit price effects that are primarily transmission congestion related
- Two cases for High VRE scenarios: with 'balanced' capacity equilibration and without (focus here is with equilibration)

Intent is to use wholesale market prices for "marginal" value assessments

Model output data available at: https://emp.lbl.gov/publications/impacts-high-variable-renewable

Regional Case Studies

SPP

- 2016 VRE Deployment:
  - **Wind 19% of generation** (~16 GW capacity),
  - Solar 0.1% of generation
- No RPS mandates driving additional renewables by 2030

NYISO

- 2016 VRE Deployment:
  - Wind 3% of generation (1.8 GW nameplate),
  - Solar 0.8% of generation (0.3 GW, incl BTM PV)
- Clean Energy Standard of 50% by 2030

CAISO

- 2016 VRE Deployment:
  - Wind 7% of generation (5.6 GW nameplate),
  - **Solar 14% of generation** (18.2 GW, incl BTM PV)
- SB 350 requires 50% RPS, projections yield 13.5% wind and 27.5% solar

ERCOT

- 2016 VRE Deployment:
  - **Wind 13% of generation** (20.3 GW nameplate),
  - Solar 0.25% of generation (1.2 GW, incl BTM PV)
- No wind/solar/carbon mandates driving deployment in 2030

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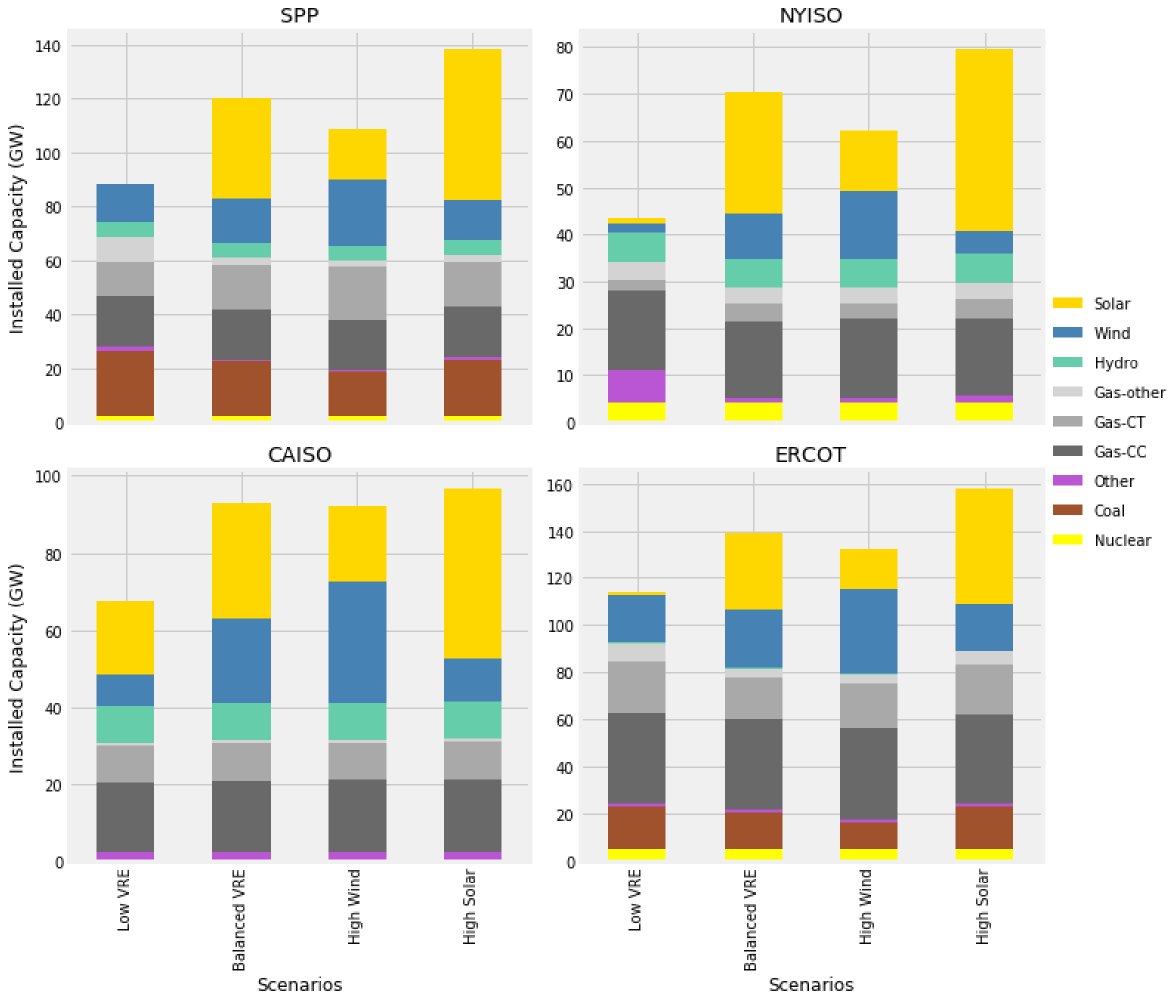
VRE Expansion Leads to Modest Retirement of Firm Capacity of 4-16%, Especially Coal, Oil and Steam Turbines

Capacity Comparison Across Regions

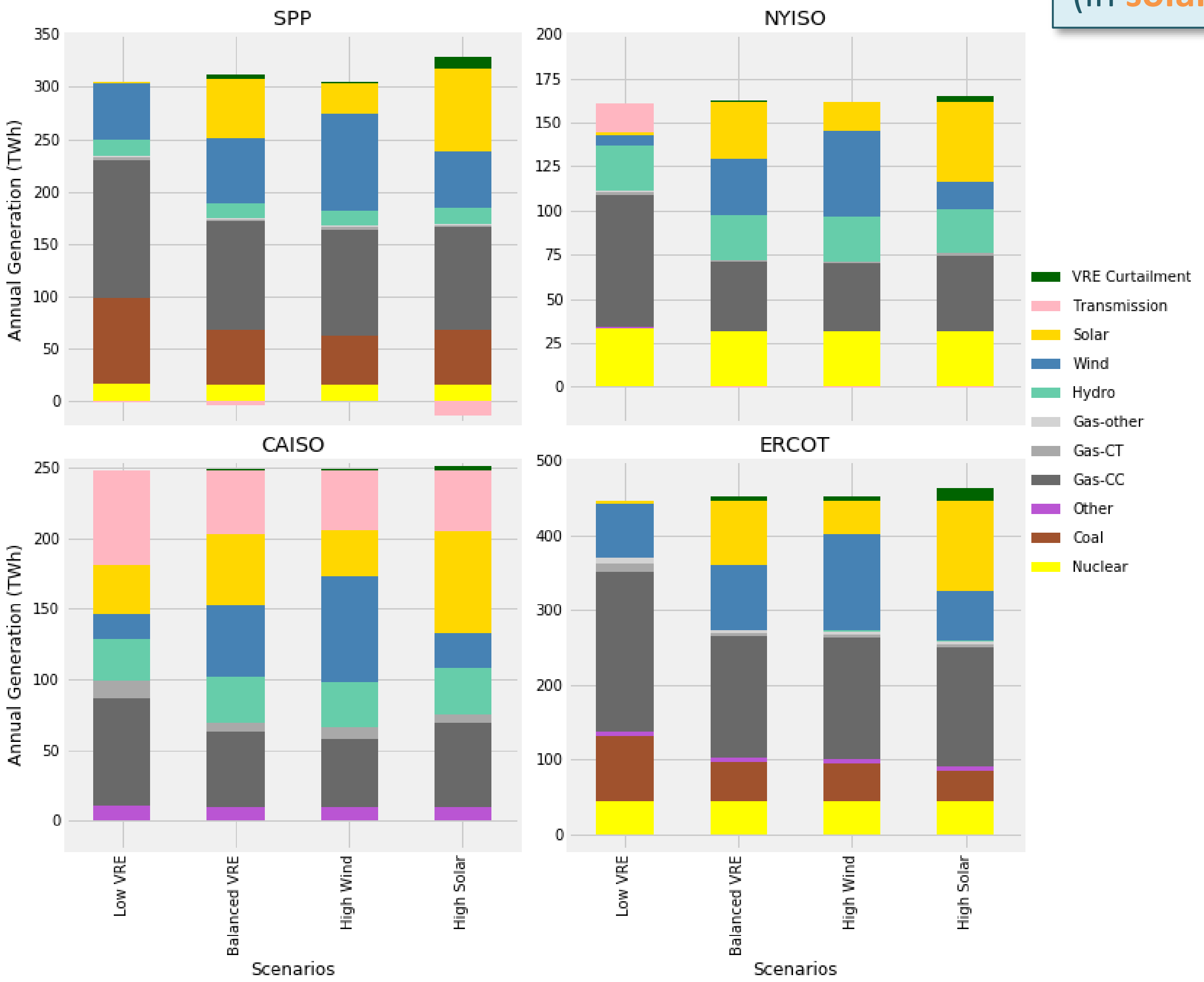


Total installed capacity increases with VRE growth as average capacity credit is 10-24% for new wind and 8-63% for new solar

- SPP: firm capacity **reduction** by 9-12%
  - Retirement of Coal (4-8GW) and Other Gas (7GW, e.g. steam turbines)
  - Partially offset by Gas CT growth (4-7GW)
- NYISO: firm capacity **reduction** by 13-16%
  - Dual Fuel (Oil) retirement (5+ GW)
  - Partially offset by Gas CT growth (1-2GW)
- CAISO: firm capacity **growth** by 2-4%
  - Little overall changes in capacity
  - Minor growth in Gas CC (0.4-0.8GW) and Gas CT (0.4GW)
- ERCOT: firm capacity **reduction** by 4-14%
  - Coal retirement largest in **wind** scenario (7GW) - none in **solar**
  - Largest Gas CT retirement in **balanced** (4GW vs. 1GW in **solar**)
  - Gas CC largely stable, growth by 1GW in **wind** scenario

Energy from VRE Primarily Displaces Coal and Natural Gas Generation

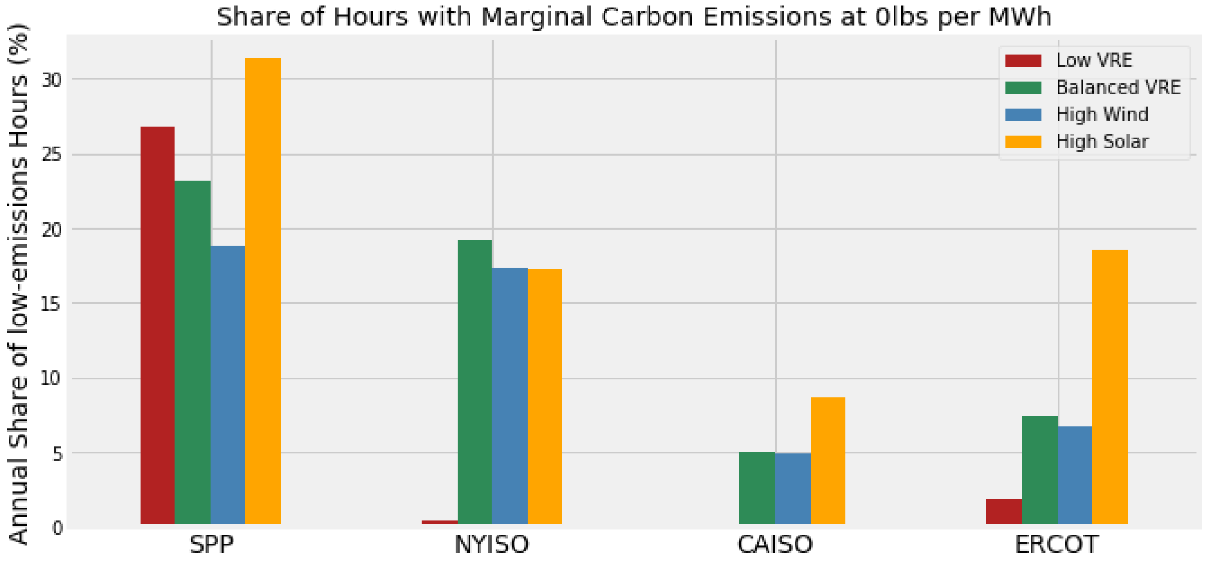
Generation Comparison Across Regions

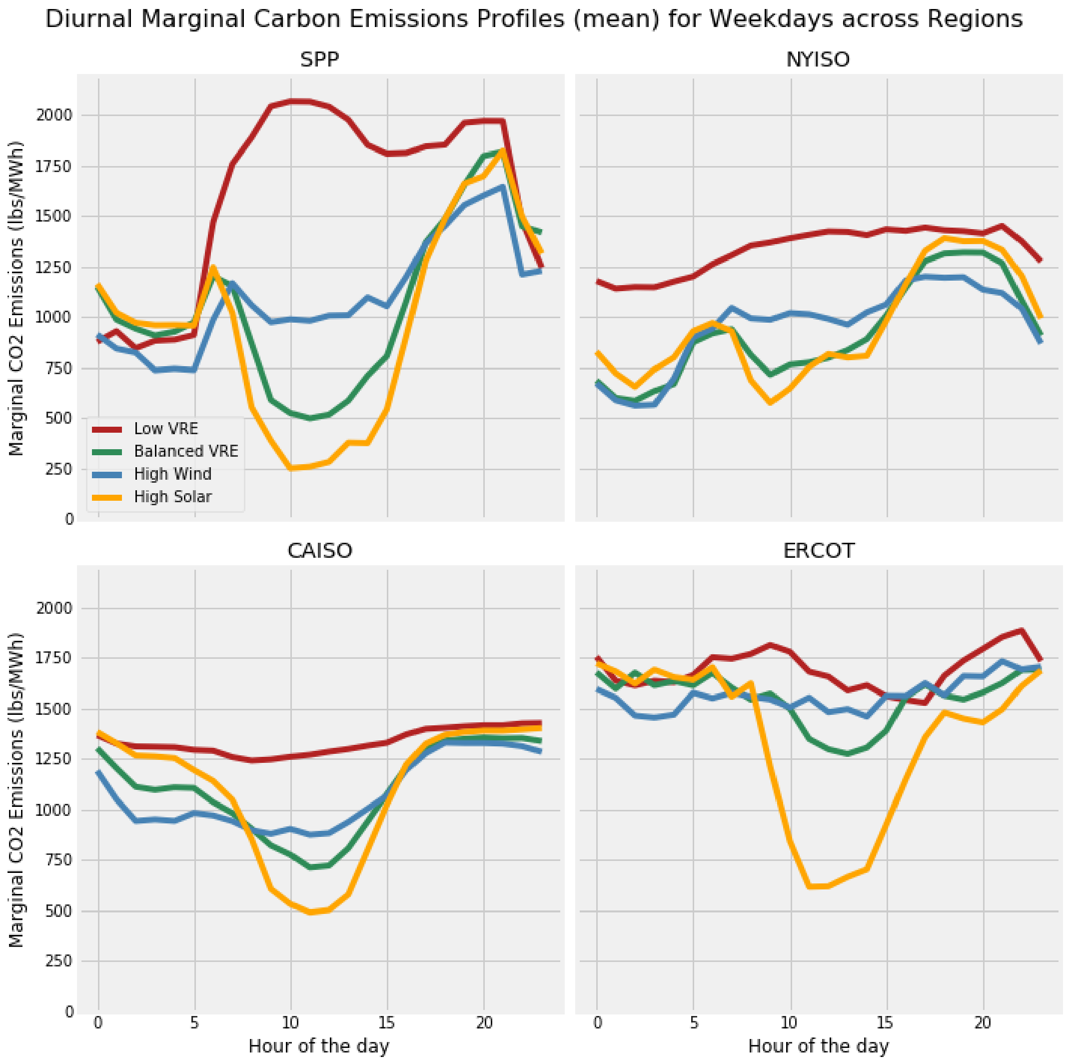


VRE generation offsets conventional generation 1-1, except when curtailed (in **solar** scenarios average VRE curtailment is 3-8% of all VRE generation)

- SPP: fossil generation reduction by 27-32%
  - Reduction in Coal and Gas CC generation (30-35TWh each)
  - Minimal changes in Gas CT
  - 11TWh of VRE curtailment, 14TWh of export in **solar** scenario
- NYISO: fossil generation reduction by 44-50%
  - Reduction in Gas CC (32-35TWh) and imports (17TWh)
  - Minimal drop in Gas CT
- CAISO: fossil generation reduction by 25-33%
  - Reduction in Gas CC (esp. in **wind** scenario: 17-28 TWh), imports (22-26 TWh) and Gas CT (4-6 TWh)
  - Difficult to assess composition of imports as we lack fuel information
- ERCOT: fossil generation reduction by 30-34%
  - Reduction in Coal (35-46TWh) and Gas CC (50-55TWh), esp. in **solar**, 60-80% Gas CT reduction (more in **wind**/**balanced**)
  - Up to 13TWh of solar curtailment, 5TWh of wind curtailment

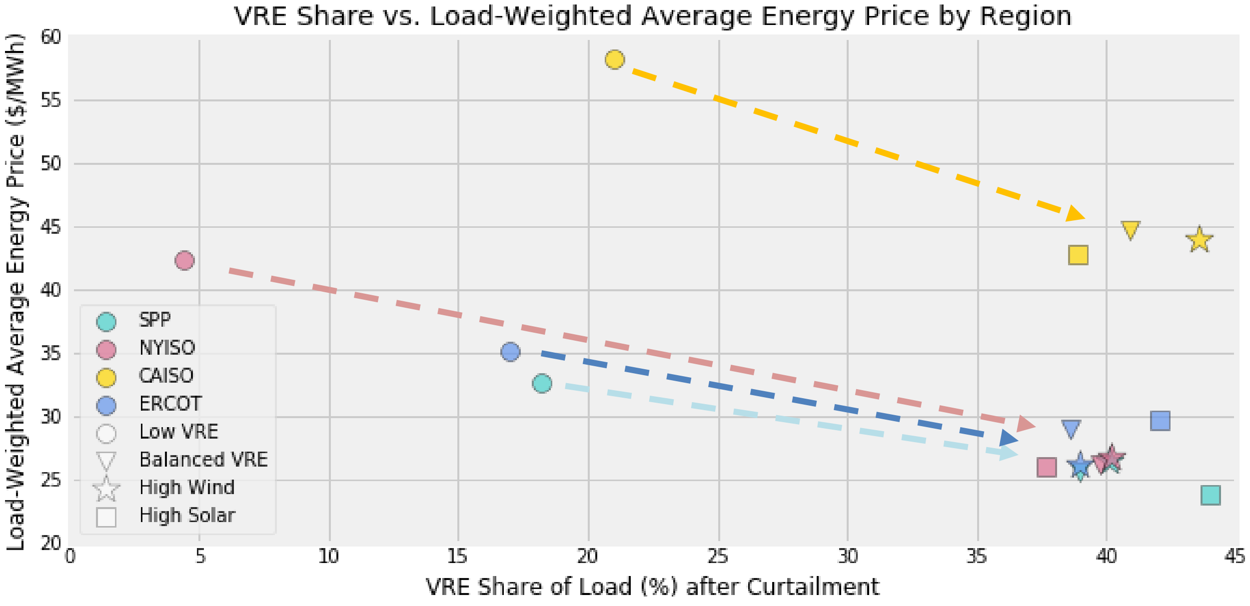
VRE Changes the Marginal Carbon Emissions Rate



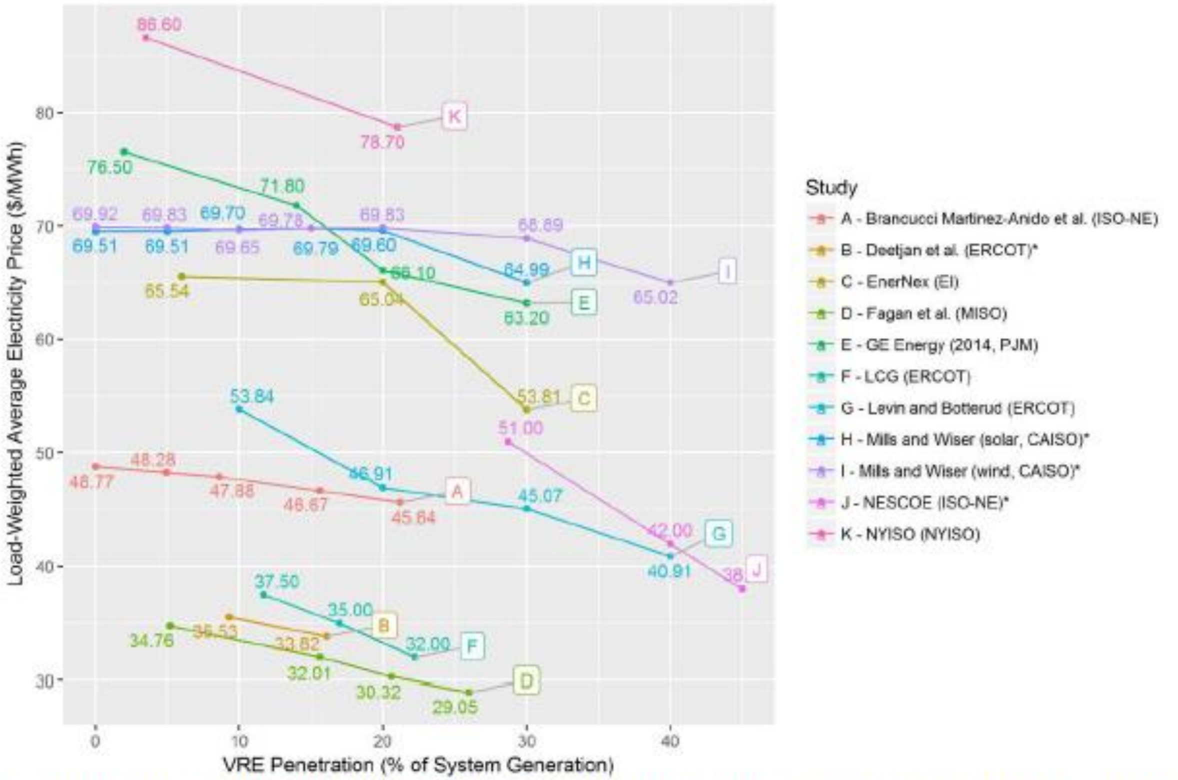


- Total carbon emissions decrease with high VRE buildout by 21-47%
- Marginal carbon emission rates decrease by 6-21% (ERCOT) to 28-38% (SPP)
- VRE shifts timing of high marginal emissions, decreases by 750-1750lbs/MWh over the middle of the day in **solar** scenario
- VRE leads to an increase in frequency of hours with very low marginal emission rates ranging from 5% of all hours in CAISO (**wind** scenario) to 31% in SPP (**solar** scenario)

Annual Average Energy Prices Decline with Increasing VRE Penetration



Load-weighted average electricity prices **decrease** with higher VRE penetration **by $5 to $16** relative to low VRE baseline, depending on scenario and region



Note: Studies denoted with an asterisk report a simple average price while the remainder report a load-weighted average price.

Figure 20. Projected Wholesale Electricity Prices with Increasing VRE Penetrations

Wiser et al 2017

Average Energy Price Reduction From VRE Falls Within Range of Previous Studies

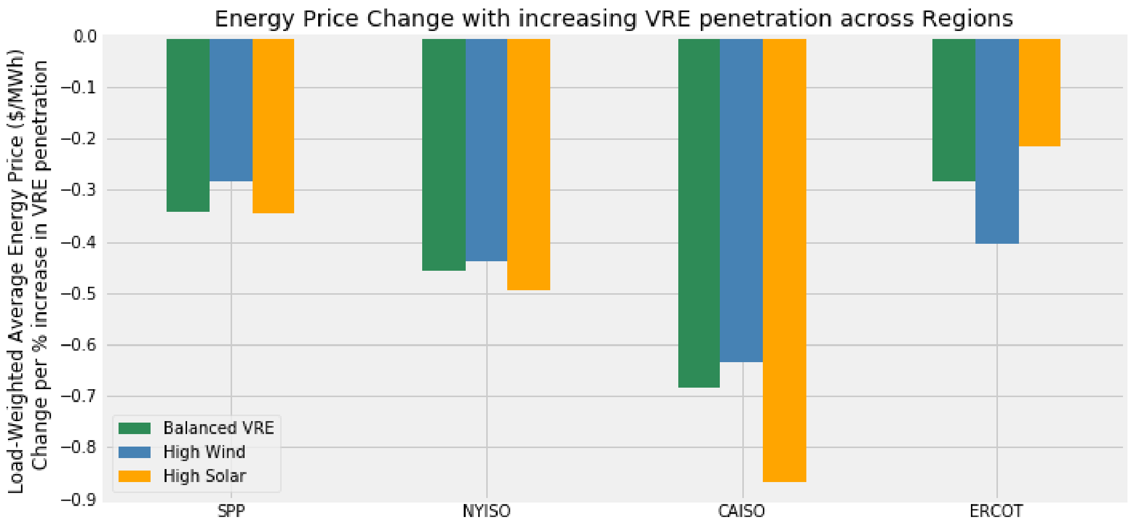


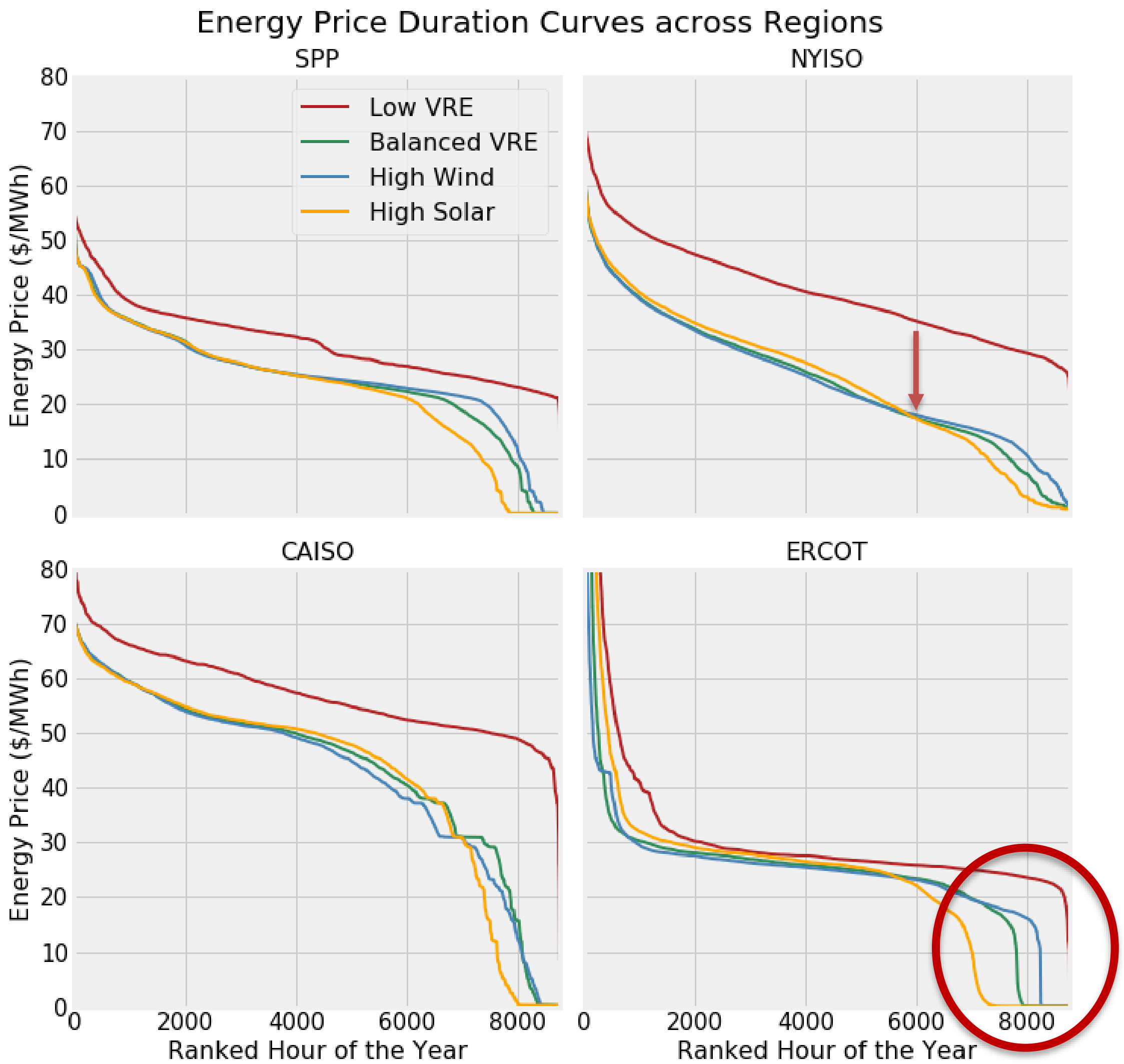
Table 5. Relationship Between Average Wholesale Electricity Price and VRE Penetration

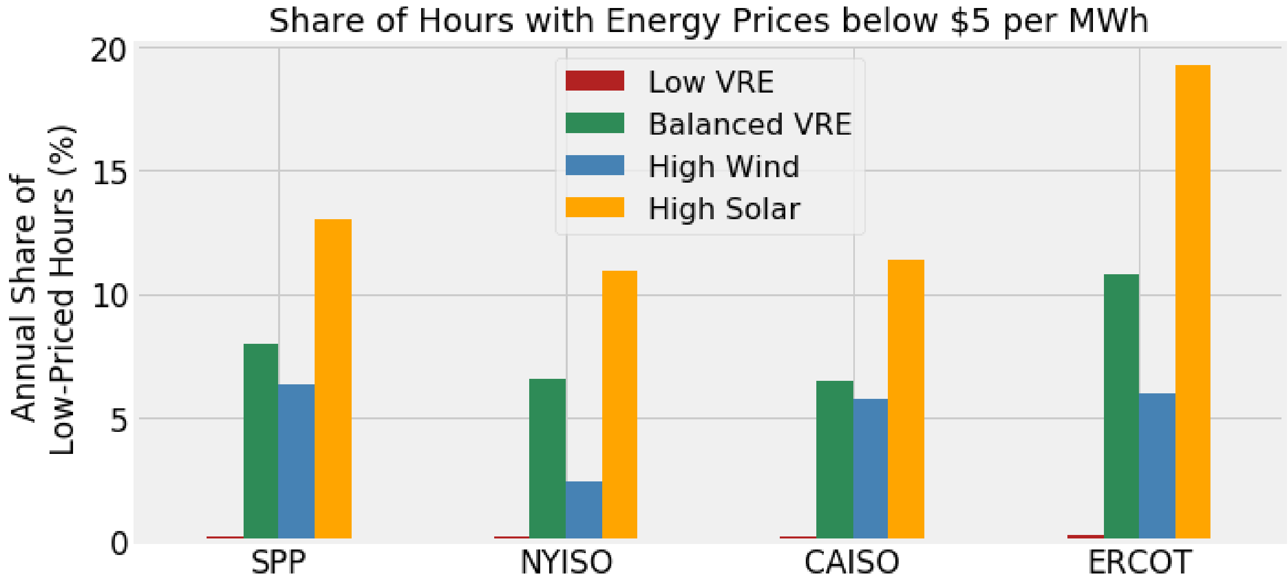
Study	Change in price ($/MWh) per % increase in VRE penetration
Brancucci Martinez-Anido et al. (ISO-NE)	-$0.15
Deetjan et al. (ERCOT)*	-$0.25
EnerNex (EI)	-$0.46
Fagan et al. (MISO)	-$0.28
GE Energy (2014, PJM)	-$0.50
LCG (ERCOT)	-$0.52
Levin and Botterud (ERCOT)	-$0.41
Mills and Wiser (solar, CAISO)*	-$0.13
Mills and Wiser (wind, CAISO)*	-$0.10
NESCOE (ISO-NE)*	-$0.80
NYISO (NYISO)	-$0.45

- A common metric for comparisons across studies is the change in price ($/MWh) per % increase in VRE penetration
- Accounting for the different starting levels of VRE penetration, the average reduction in electricity is **$0.21-$0.87/MWh** for each additional % of VRE penetration ($0.19-$.81/MWh for pre-curtailment VRE)
- CAISO has greatest reduction due to carbon costs and relatively small incremental VRE generation growth
- Decrease in average prices will reduce profitability of inflexible generators that are fully exposed to those prices (nuclear, solar, wind, to some extent coal and gas steam)
- Our observation falls roughly in the range of established literature

Wiser et al 2017

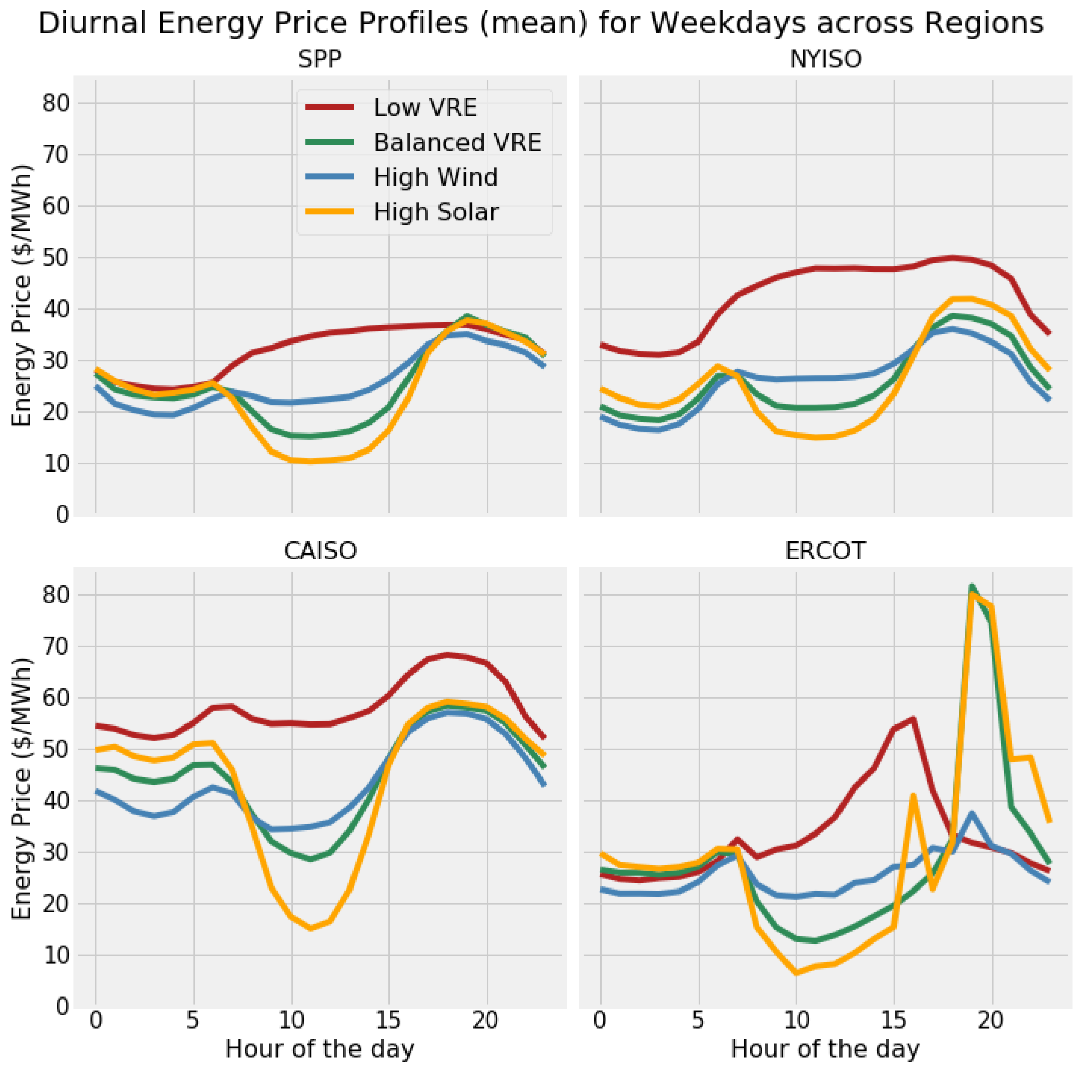
Low Energy Prices Become More Frequent Under High VRE Scenarios





- 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**

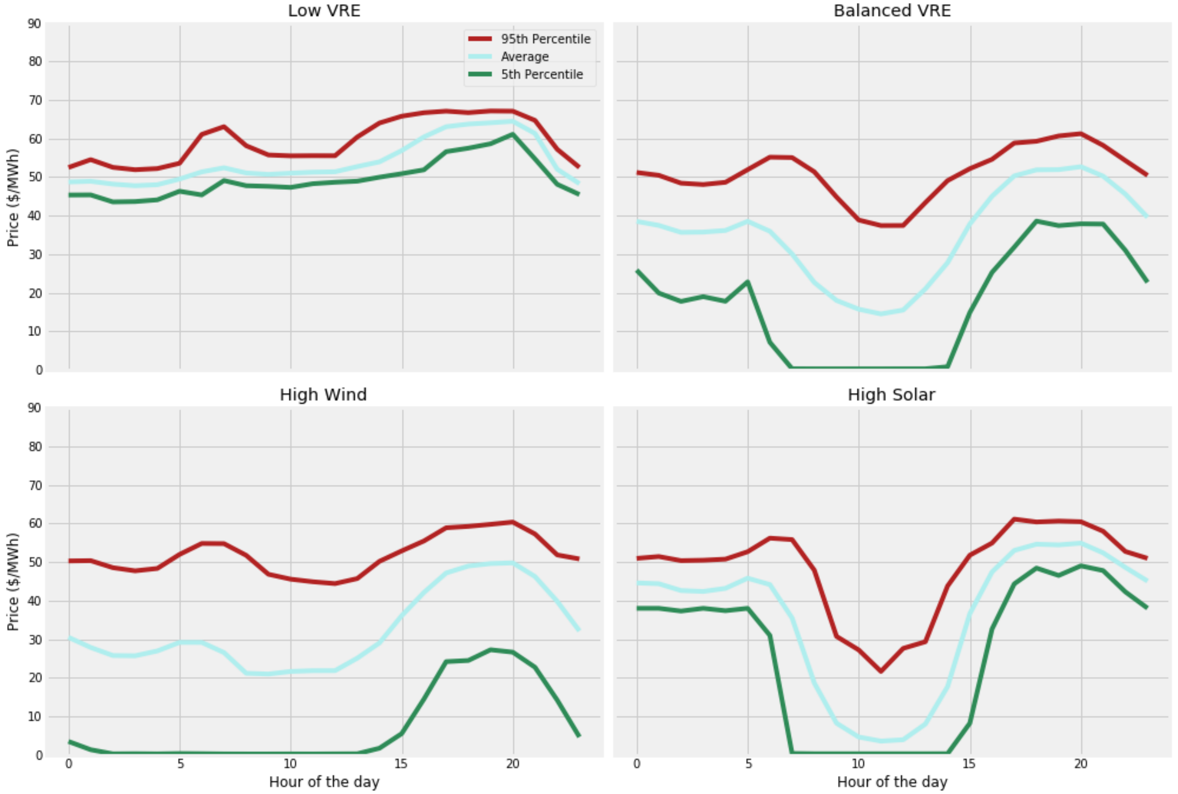
High VRE Significantly Alters Diurnal Price Profiles, Particularly With High Solar

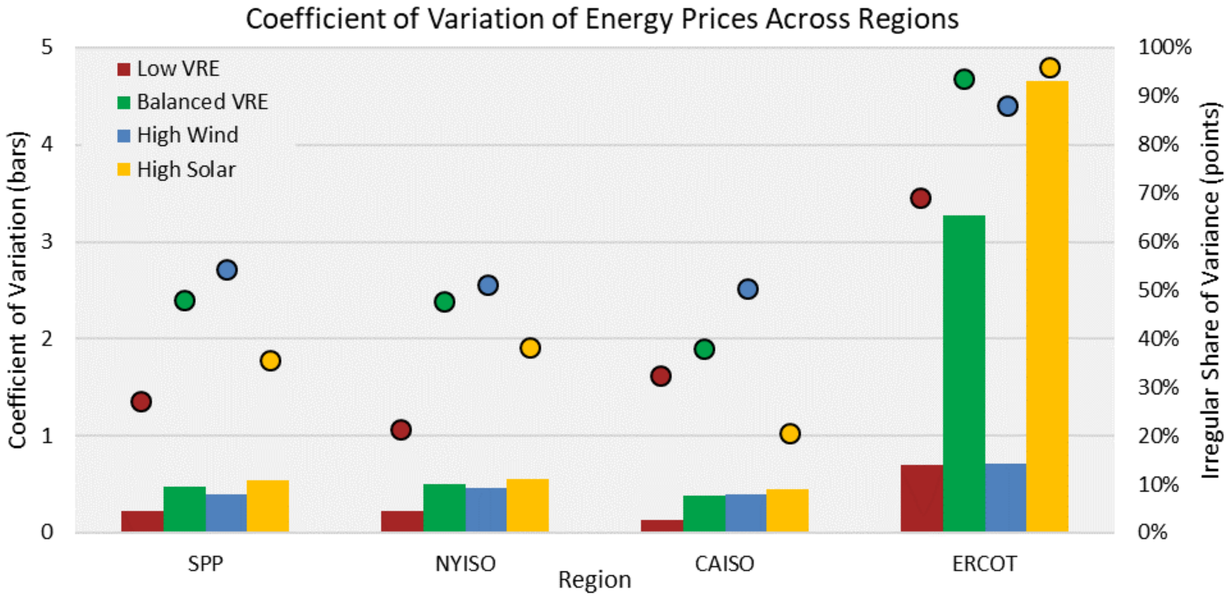


- Substantial decrease in prices over the middle of the day in **solar** scenarios across all regions
- Diurnal profiles vary by season
  - **Morning:** **wind** vs **low VRE** scenario in CAISO:
    - -$25/MWh in Spring, but only -$10/MWh in Fall and Winter
  - **Afternoon:** **solar** vs **low VRE** scenario in NYISO:
    - -$30/MWh in Spring and Summer, but only -$15/MWh in Winter
  - **Evening:** **balanced** / **solar** vs **low VRE** scenario in ERCOT:
    - +$180/MWh in Summer (driven by few high-priced hours), but only +$5/MWh in Winter
- Price peaks remain across most seasons in the early evening at levels similar to **low VRE** scenario

High VRE Increases Price Volatility; Prices Are Most Irregular with High Wind

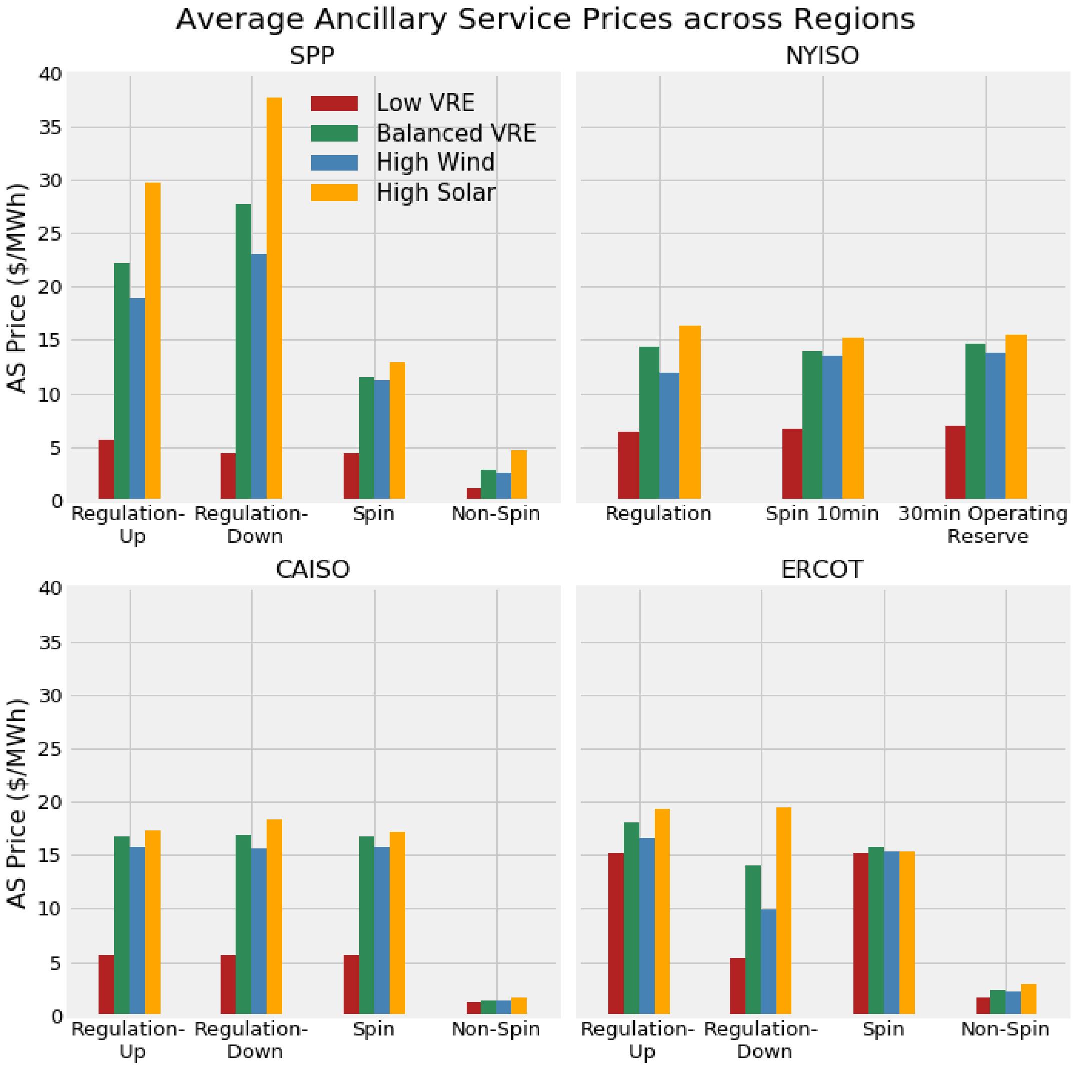
Price Distribution in CAISO in Spring





- Wider range in **wind** scenario during early morning hours
- Change in average diurnal profile in **balanced** scenario & 5^{th}-95^{th} range increases during the middle of the day
- Coefficient of Variation is standard deviation of prices normalized by mean energy price to facilitate cross-regional comparison
- High volatility in ERCOT in part due to few high priced hours ($1000-$9000/MWh) due to Operating Reserve Demand Curve
- Total price volatility increases with VRE penetration, largest with **solar**
- Irregularity of prices (variability not captured by diurnal profiles, seasonal shifts and weekdays/weekends) is highest in **wind** scenarios

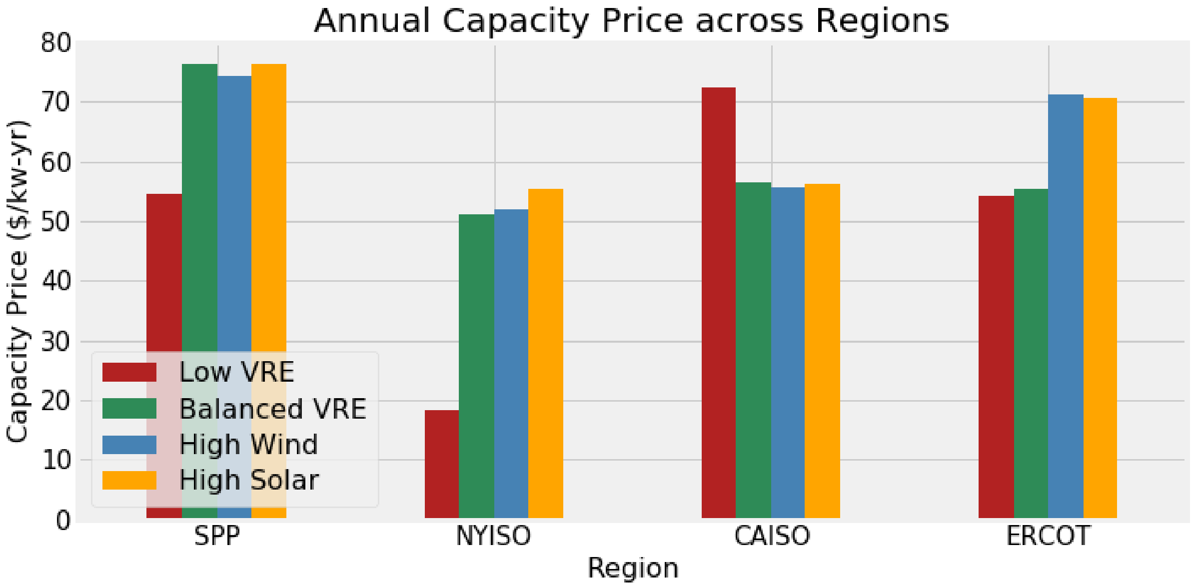
High VRE Leads to an Increase in Ancillary Service Prices

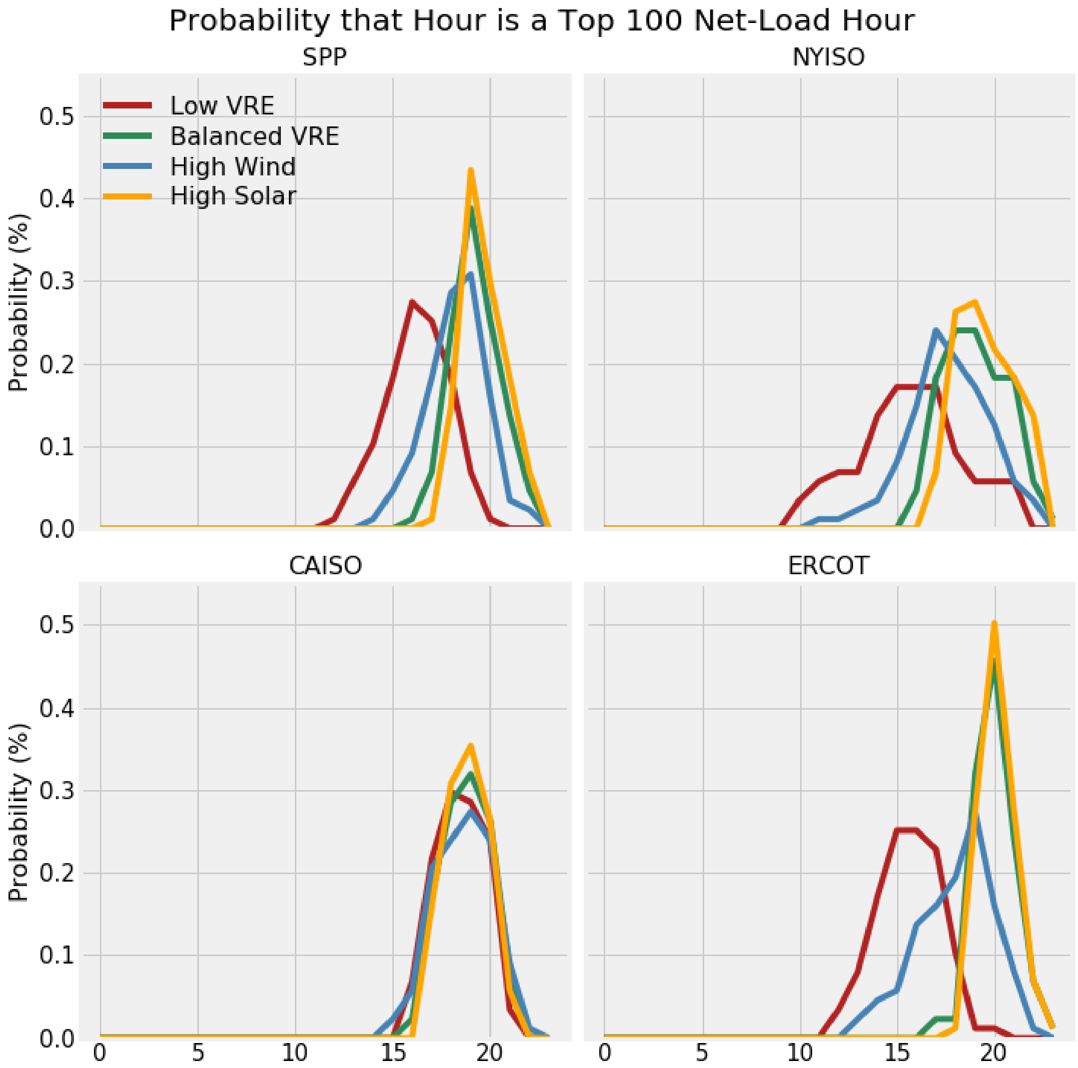


- Average prices for regulation (up and down) and spinning reserves increase by 2-8x across most regions in high VRE future to $15-$38/MWh due to high opportunity costs at low-net load levels
- Non-spinning reserves tend to remain at lower prices
- High **solar** penetrations often lead to the strongest increase, with peak prices above $190/MWh in CAISO across all AS-types
- In SPP, downward regulation prices reach occasionally $200/MWh in all high VRE scenarios
- Diurnal AS price profiles and their peaks can change significantly, as do price ranges

Increases for regulation reserve requirements with VRE are consistent with previous region-specific studies
(an increase in the range of 1-1.5% of hourly VRE generation)
VRE was not allowed to provide AS

High VRE Has Modest Impacts on Capacity Prices; More Pronounced Shift In Timing of Peak Periods





- Mixed trends in annual averages, **solar** often leads to higher prices
- Depending on region, top net-load hours are concentrated over fewer hours of the day and pushed later into the evening, especially in **solar** scenarios
- Top 100 net-load hours are spread however over more days (and months) in the high VRE scenarios in comparison to the low VRE scenario (from 22 to 45 days in ERCOT).

Overview of Briefing

- Background: Evidence of VRE-induced Price Changes and Theory
- Research Motivation and Objective: Examples of Electric-Sector Decision Making
- Analytical Framework for Quantitative Assessment
- Key Findings: Changes at High VRE Penetrations
- Discussion and Outlook

Conclusion and Discussion

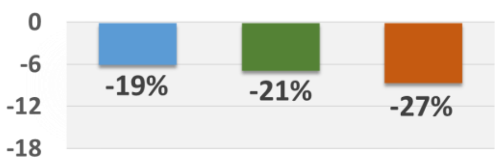
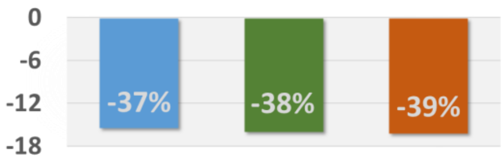
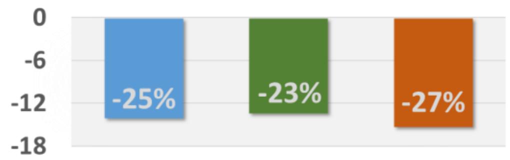
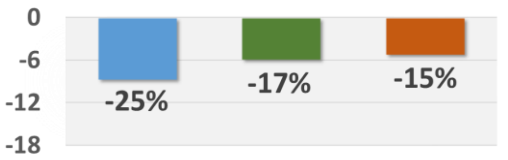
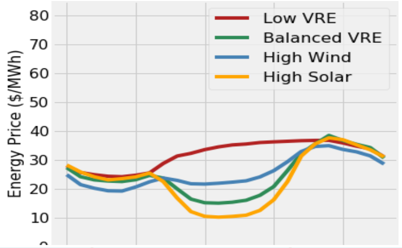
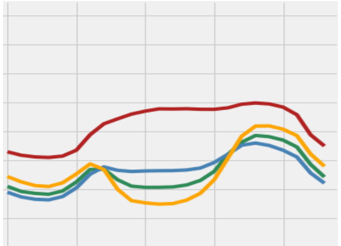
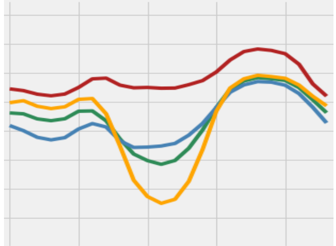
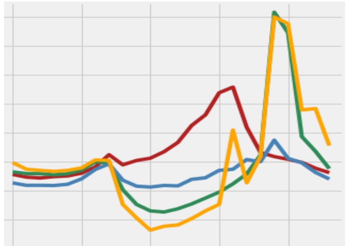
- VRE additions enable modest firm capacity and strong non-VRE generation reduction
- Growth in VRE can decrease overall average wholesale market prices by $5-$16/MWh
- Changing timing of cheap/expensive electricity and regularity/predictability of patterns:
  - Growth in frequency of very low priced periods (up to 20% of all hours in ERCOT)
  - Changing diurnal patterns especially with high solar
  - Increase in irregularity of wholesale prices especially with high wind
- Lower average energy prices will increase relative importance of rising capacity and ancillary service prices
- Magnitude and importance of these shifts depends on response of other market participants (changing aggregate load shapes, DR participation, storage)
- Results sensitive to our assumptions:
  - Not modeling intra-regional congestion, limited VRE leakage to neighboring regions
  - Fuel price and emission cost deviations impact optimal generator portfolio and marginal prices
  - Focus on single exemplary year 2030 that doesn't capture inter-annual variation or longer-term evolution of electric system

Outlook

- In written report (and appendix) we qualitatively highlight some of the possible impacts of changing wholesale price-patterns on other demand- and supply-side decisions that should be considered by decision-makers that have to invest in long-lasting assets
- While the decision-making processes and considerations may differ between regulated and de-regulated regions of the country, analysis of the marginal value of different resources can be informative in either case.
- These simulated wholesale prices are the foundation for planned quantitative evaluations to explore to explore how various demand- and supply-side decisions might be affected by changes in the future electricity supply mix

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		

Questions?

A full technical report and underlying data sets are available at:

https://emp.lbl.gov/publications/impacts-high-variable-renewable

Contact:

- Joachim Seel:
  jseel@lbl.gov 510-486-5087

- Andrew Mills
  admills@lbl.gov 510-486-4059

- Ryan Wiser
  rhwiser@lbl.gov 510-486-5474

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Download all of our other solar and wind work at:

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Appendix 1: Demand-Side Asset Implications

Decision	Relevant Change with High VRE	Potential Change in Decision
What combinations of energy efficiency measures are most cost effective? Commercial AC vs. residential lighting	- High solar lowers prices on hot summer days, but not at night	Shift emphasis from commercial office AC to residential and street lighting
Electrification of gas end-uses: Which is better: electric or gas water heaters?	- VRE lowers carbon content of electricity - VRE, especially wind, needs more flexible load	Electric hot water heaters (with DR capabilities) may be better than gas in high wind generation areas
What kind of demand response services are most cost-effective?	- Less predictability of when high price periods will occur - Need load to increase during over-generation	Shorten notification periods for DR, identify ways for DR to increase load, differentiate DR services
Where should electric vehicle charging infrastructure be built? Commercial or residential locations? What kind of charging technology should be deployed?	- VRE requires more flexibility - High solar lower prices in afternoons	Increased value in vehicle-2-grid and, with high solar, day-time charging infrastructure (i.e. at commercial locations rather than residential)
How efficient are different retail rate designs?	- Wholesale prices will shift with VRE, with indirect effects for retail rates	Under time-varying rates, pricing periods and levels will shift with high VRE
Should an advanced commodity production process be designed to run continuously or in batches?	- High VRE increases periods with low or negative prices	Promote research on other processes that can use cheap electricity over short periods (e.g., air separation, oil refinery, pulp and paper, irrigation pumping, recycle smelting)

Appendix II: Supply-Side Asset Implications

Decision	Relevant Change with High VRE	Potential Change in Decision
How large of an incentive is needed (if at all) to ensure revenue sufficiency for existing nuclear plants? Is it cost-effective to increase their flexibility?	- VRE lowers off-peak prices and requires more flexibility	Inflexible nuclear plants are less valuable in high VRE regions
Is a highly flexible reciprocating engine more cost-effective than a CCGT?	- VRE requires more flexibility, lowers wholesale prices	Increased role for reciprocating engines in high VRE future
Is it cost-effective to build new energy storage?	- VRE increases the volatility of prices and solar narrows peaks	Increased role for storage, with duration depending on VRE type
What are the impacts of alternative water flow regimes in hydropower relicensing?	- VRE increases volatility of prices and changes timing	Alternative flow regimes may have greater impact on projected revenues
Where should wind and solar assets be sited and how should project design evolve?	- VRE will decrease wholesale energy prices at time of generation if output is highly correlated	Shift location to areas that are better aligned with high-priced hours, adopt south-western orientation of PV modules, taller wind turbine towers with lower specific power ratings, colocation with energy storage