Energy Technologies Area Lawrence Berkeley National Laboratory

Impacts of Variable Renewable Energy on Bulk Power System Assets, Pricing, and Costs

Ryan Wiser, Andrew Mills, Joachim Seel
Todd Levin and Audun Botterud

Report Summary
November 2017

This work was supported by the Transmission Permitting & Technical Assistance Division of the U.S. Department of Energy's Office of Electricity Delivery and Energy Reliability under Lawrence Berkeley National Laboratory Contract No. DE-AC02-05CH11231, and by Argonne National Laboratory.

Two Recent National Lab Reports

(1) Covered in this presentation

Impacts of Variable Renewable Energy on Bulk Power System Assets, Pricing, and Costs

Authors:

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[1] Lawrence Berkeley National Laboratory

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(2) Not fully covered in presentation

Power Plant Retirements: Trends and Possible Drivers

Authors:

Andrew Mills, Ryan Wiser, Joachim Seel

Energy Analysis and Environmental Impacts Division
Lawrence Berkeley National Laboratory

This work was supported by the Transmission Permitting & Technical Assistance Division of the U.S. Department of Energy's Office of Electricity Delivery and Energy Reliability under Lawrence Berkeley National Laboratory Contract No. DE-AC02-05CH11231.

Content: [1] basic trends in retirements by project age, size, heat rate, emissions; [2] correlates to regional retirement percentages

Project Objectives and Team

Dual Objectives

- Feed content into *DOE Staff Report on Electricity Markets and Reliability*
- Conduct new analysis and literature synthesis that seeds a more comprehensive work scope after DOE report

Lab Team

- LBNL: Wiser, Mills, Seel
- ANL: Levin, Bottered
- Text box & review from NREL

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Presentation Scope

Summarize findings from LBNL/ANL report

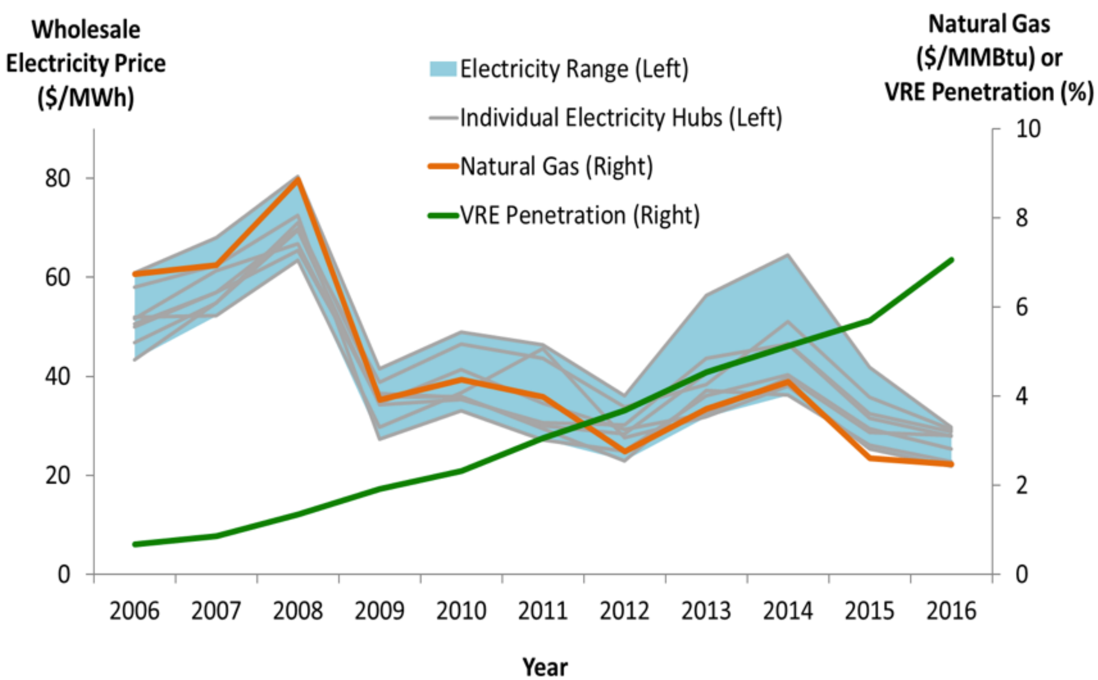
- Introduction and Scope
- Economic Underpinning and Expectations
- Historical Observed Impacts of VRE on the Bulk Power System
- Prospective Future Impacts of VRE on the Bulk Power System
- System Value and System Costs of Variable Renewable Energy

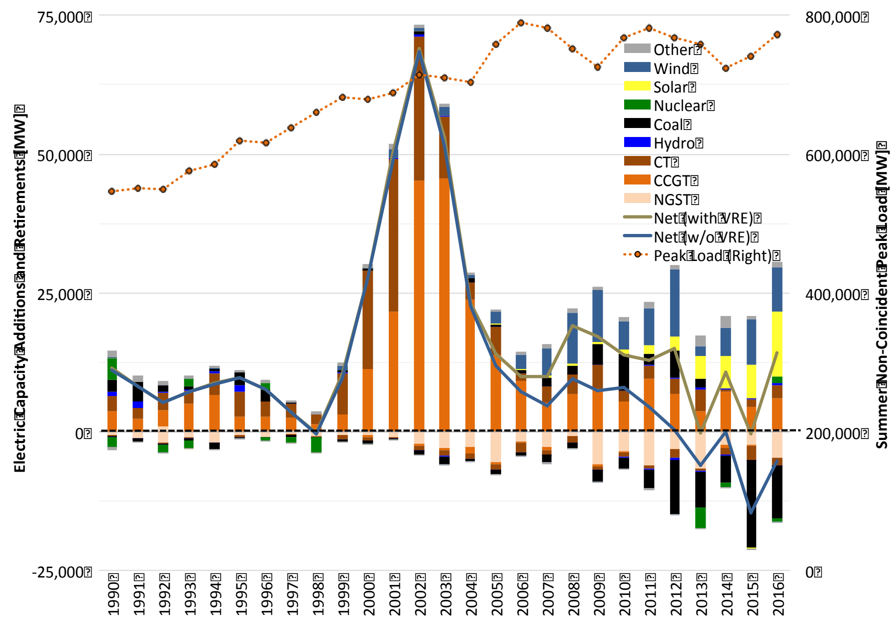
Highlight future work to build on this foundation

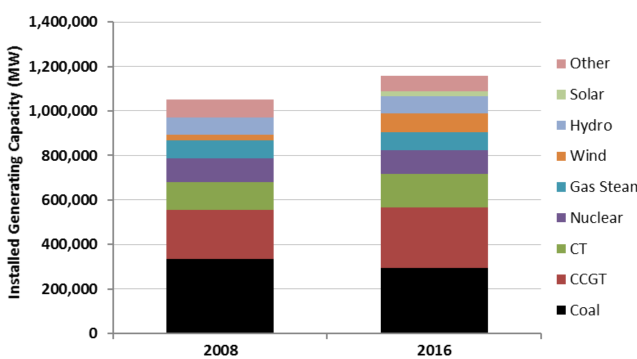
Introduction and Scope

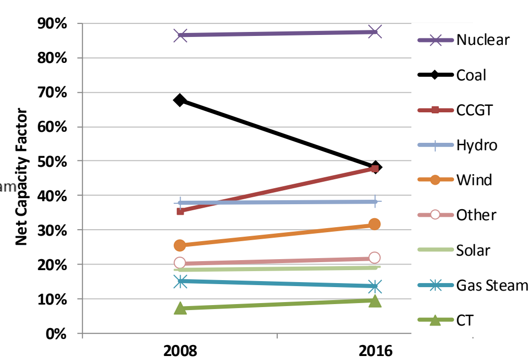
Background

Wholesale power pricing and the composition and operation of the bulk power system have witnessed changes in recent years









Concurrent with these trends has been growth in VRE, leading to the question: to what degree are VRE and the incentives supporting VRE contributing to these trends?

Objectives and Paper Scope

Synthesize available literature, data & analysis on the degree to which growth in variable renewable energy (VRE) has impacted or might impact bulk power system assets, pricing, and costs

- wholesale power market pricing
- operation of other power plants, and
- incentives for generation asset retirement and investment

Where possible, frame impacts of VRE within the context of other possible drivers for some of the same trends; we do not analyze impacts on specific power plants, instead focusing on national and regional system-level trends

Finally, consequent to the unique characteristics of VRE, highlight the implications of the paper's findings for the 'system value' or 'system costs' of VRE

Caveats to Project and Paper Scope

Primarily literature and data synthesis; analyzing the impacts of VRE on bulk power markets is a complex area and there is much more work to be pursued in all of the areas covered in this report

Report does not comprehensively address issues related to short time-scale variations in VRE and the technical characteristics of VRE as they affect power system reliability and VRE integration

Report does not address market design and compensation mechanism design under a changing mix of generation, a focus of the recent FERC conference and considerable other additional work

We seek to draw generalizable findings, but all of the issues addressed are context dependent, affected by underlying generation mix of the system, amount of VRE, and the design and structure of the bulk power system

Each chapter ends w/ section on further research needs

Economic Underpinning and Expectations

VRE Characteristics, Expected Impacts

Extensive global and U.S. literature demonstrates general tendencies depicted at right, 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

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

Impacts of VRE Policies and Incentives

- Useful to separate the distinct effects of policy support for VRE (or any other type of generation): one that affects deployment, and the other that impacts bidding behavior
- As it relates to bidding behavior, PTC and RPS create incentives for VRE plant owners and purchasers to bid that generation into wholesale markets at negative prices
  - Wind and solar are not the only resources that bid negative prices in wholesale electricity markets
  - Nor are wind and solar the only resource that benefit from federal, state, or local incentives of one form or another
- Whether either of these impacts—the deployment impact or the bidding impact—is considered a ‘market distortion’ depends on perspective

Historical Observed Impacts of VRE on the Bulk Power System

Chapter Content

Impacts of VRE on average wholesale prices

- Literature review of previous U.S.-based assessments
- Own analysis focused on CAISO and ERCOT

Impacts of VRE on wholesale price variability

- Negative prices: frequency, impacts, causes
- Price volatility, high prices, temporal patterns *[see full report]*
- Locational impacts: influence of transmission on specific hubs

Impacts of VRE on recent thermal-plant retirements

Directions for future research

Focus on LMPs, not capacity or AS; where possible, impacts placed within a broader context of other drivers for wholesale price patterns

Average Price Impacts: Literature Review

Low marginal-cost generation (and negative bidding) will push the supply curve out, reducing wholesale prices at least in the near term; several studies have used historical prices and statistical methods to estimate this VRE "merit order" effect

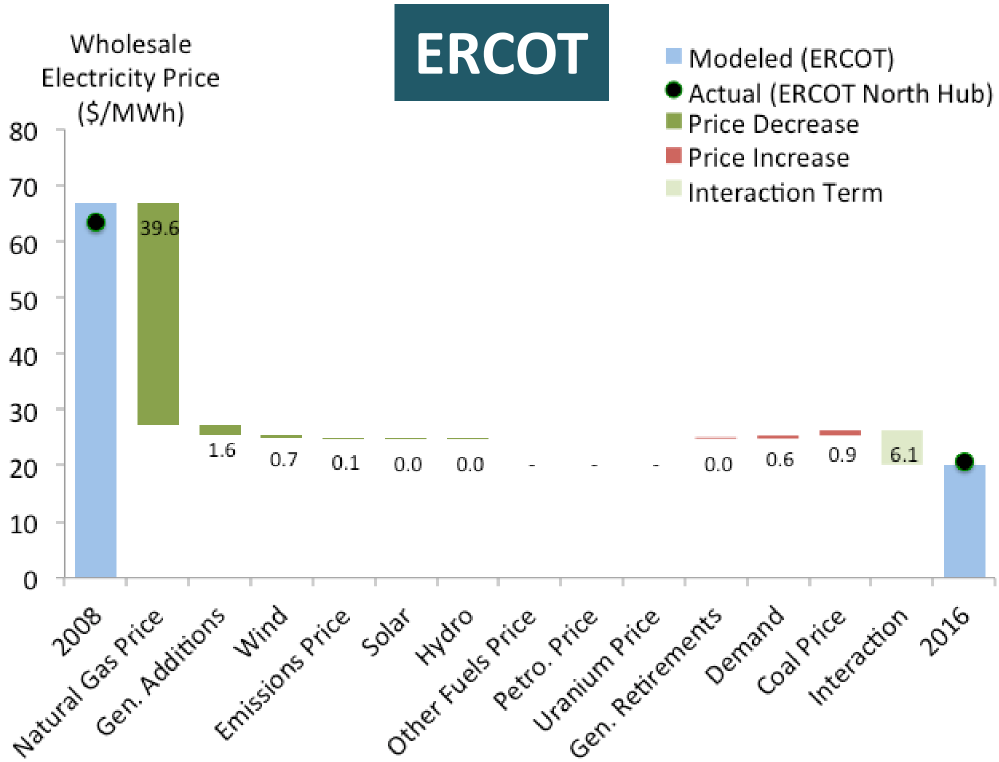
Study	Applicable Region	Time Period	Average VRE Penetration (% of demand)	Decrease in Average Wholesale Price from Average VRE
Woo et al. 2011	ERCOT	2007-2010	Wind: 5.1%	Wind: $2.7/MWh (ERCOT North) $6.8/MWh (ERCOT West)
Woo et al. 2013	Pacific NW (Mid-C)	2006-2012	N/A	Wind: $3.9/MWh
Woo et al. 2014	CAISO (SP15)	2010-2012	Wind: 3.4% Solar: 0.6%	Wind: $8.9/MWh Solar: $1.2/MWh
Woo et al. 2016	CAISO (SP15)	2012-2015	Wind: 4.3% Solar: 2.6%	Wind: $7.7/MWh Solar: $2.1/MWh
Gil and Jin 2013	PJM	2010	Wind: 1.3%	Wind: $5.3/MWh
Wiser et al. 2016[a]	Various regions	2013	RPS energy: 0%-16% depending on the region	RPS energy: $0 to $4.6/MWh depending on the region
Jenkins 2017[b]	PJM	2008-2016	N/A	Wind: $1-2.5/MWh
Haratyk 2017[b]	Midwest Mid-Atlantic	2008-2015 2008-2015	N/A	Wind: $4.6/MWh Wind: $0/MWh

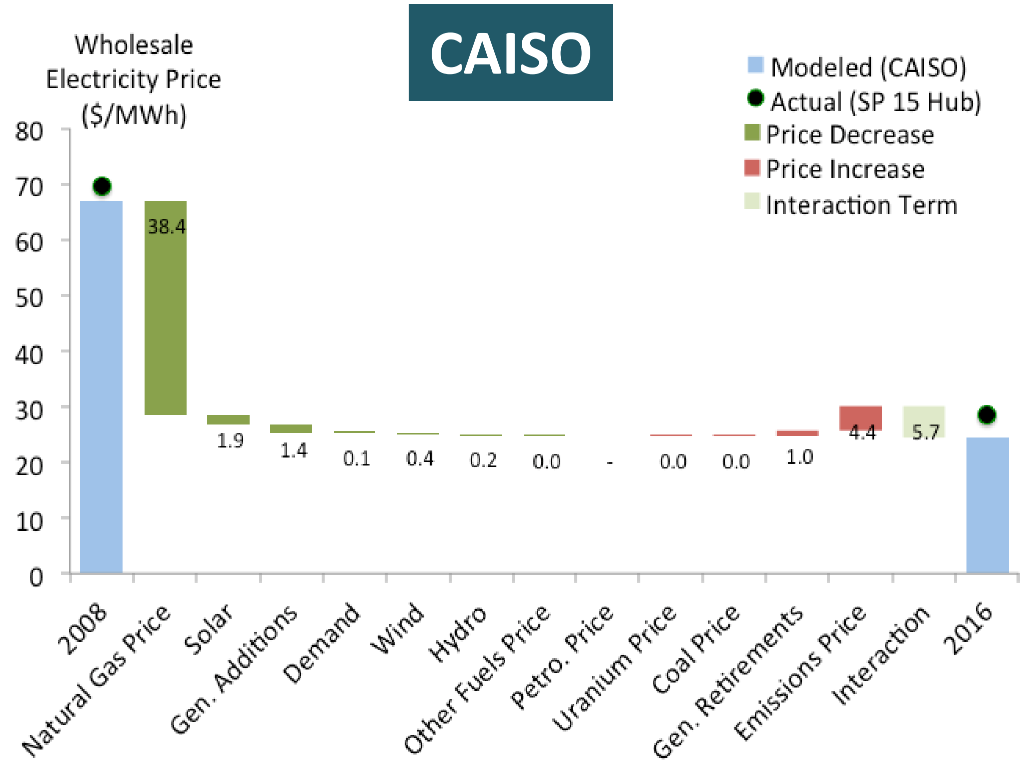
Notes: a – Price effect is estimated impact of RPS energy relative to price without RPS energy in 2013 before making adjustments due to the decay effect discussed by the authors. b – Decrease in average wholesale price is based on change in wind energy from 2008-2016 (Jenkins 2017) or 2008-2015 (Haratyk 2017), rather than the decrease from average wind reported in other rows.

See also: Makovich and Richards (2017), Hibbard, Tierney, and Franklin (2017), Hogan and Pope (2017)

Our Analysis Shows Limited VRE Impact on Annual Average Wholesale Prices

Natural gas price decline is the dominant driver in reduced average annual wholesale prices from 2008 to 2016 in ERCOT and CAISO; VRE impacts are modest, in part due to relatively flat supply curve

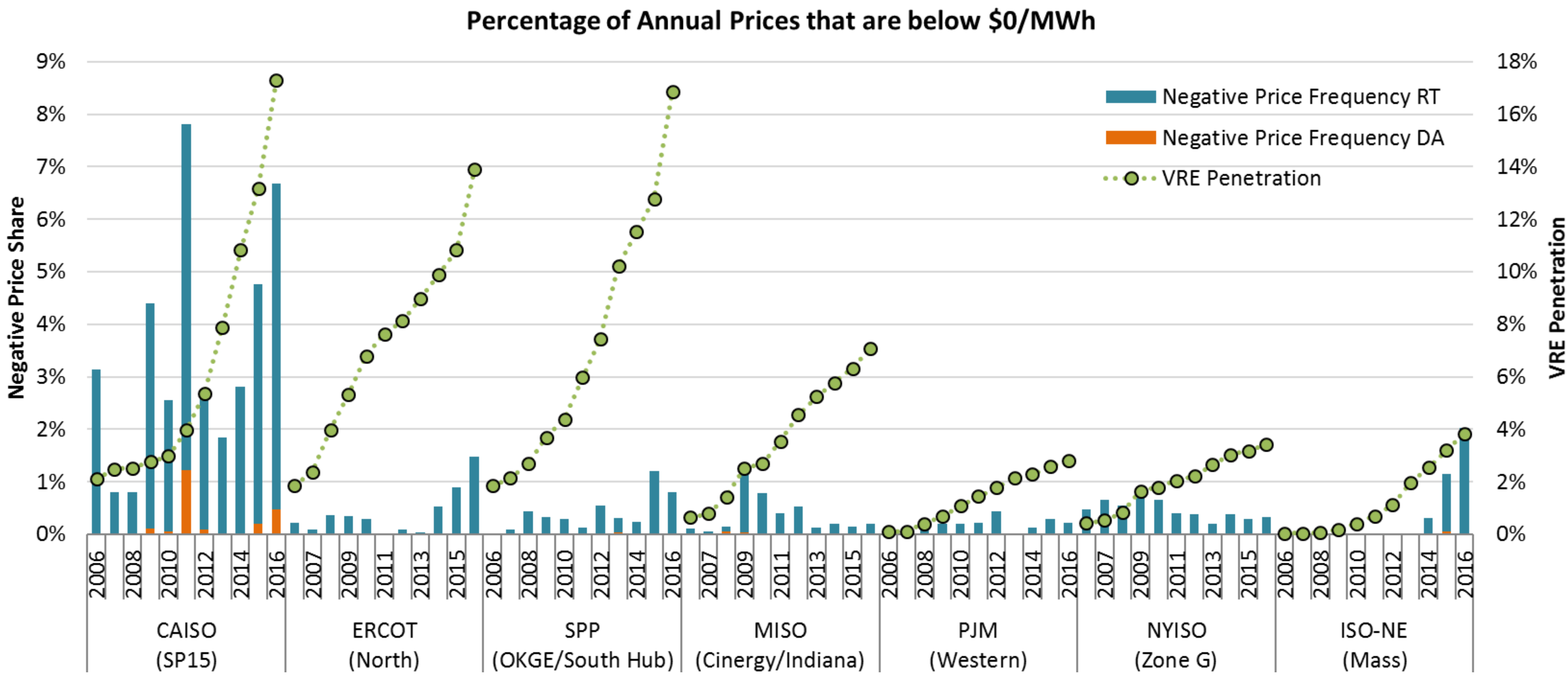




Used simple fundamental "supply curve" model to estimate wholesale prices in 2016 and 2008, and factors that drove prices down over this period; see details in full report and appendix

Negative Prices at Many Large Trading Hubs Are Rare, but Increasing in Some with VRE

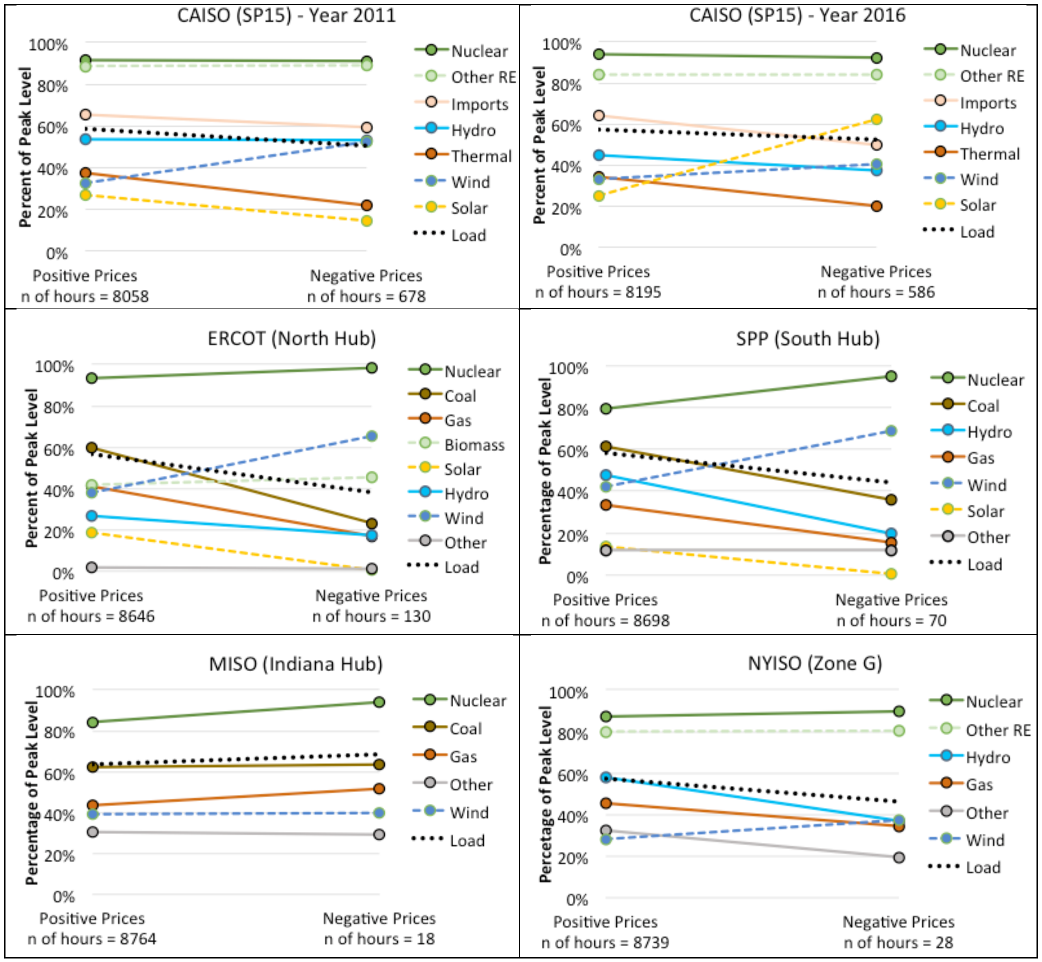
CAISO unique in high frequency of negative prices; VRE does appear to play a role, but not exclusively, in driving these events

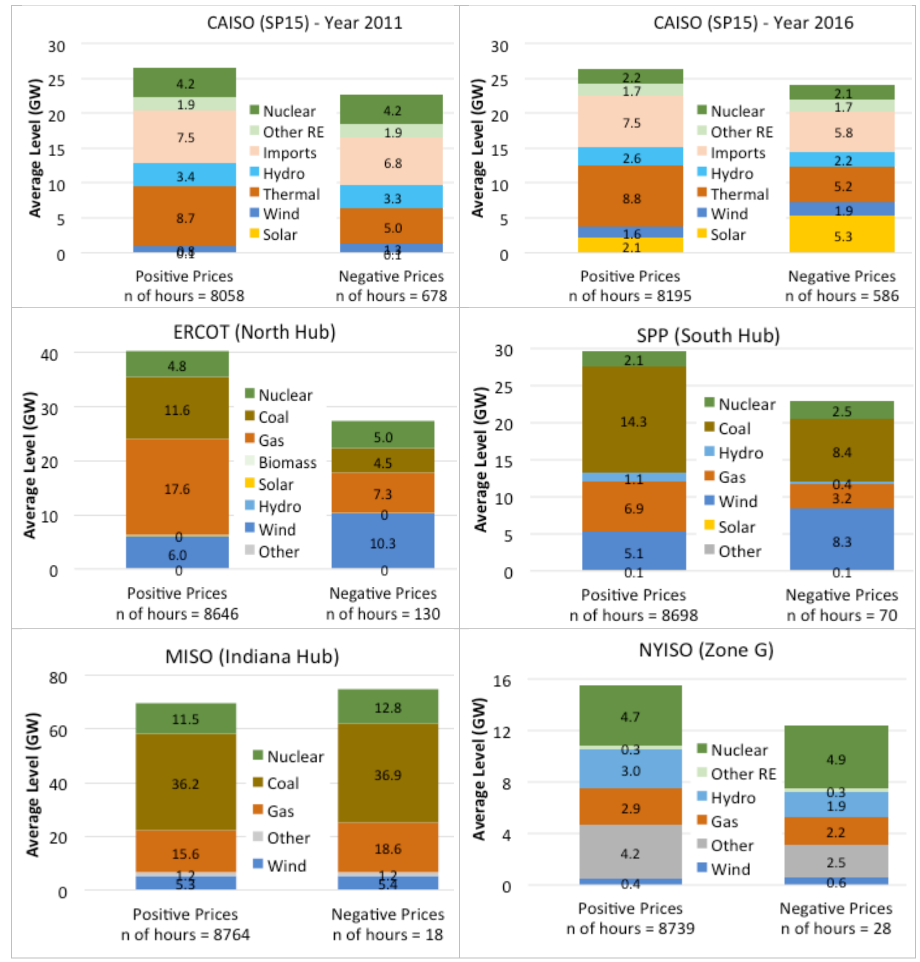


Focuses on selected major trading hubs; negative prices almost non-existent in day-ahead market (though lower average real-time prices may also lower average day-ahead prices)

VRE and Other Inflexible Generation Contributes to Negative Price Events

Negative price hours generally correlated with low system load & higher VRE; flexible generation produces less in these hours; nuclear insensitive to negative pricing, thereby contributing to these events

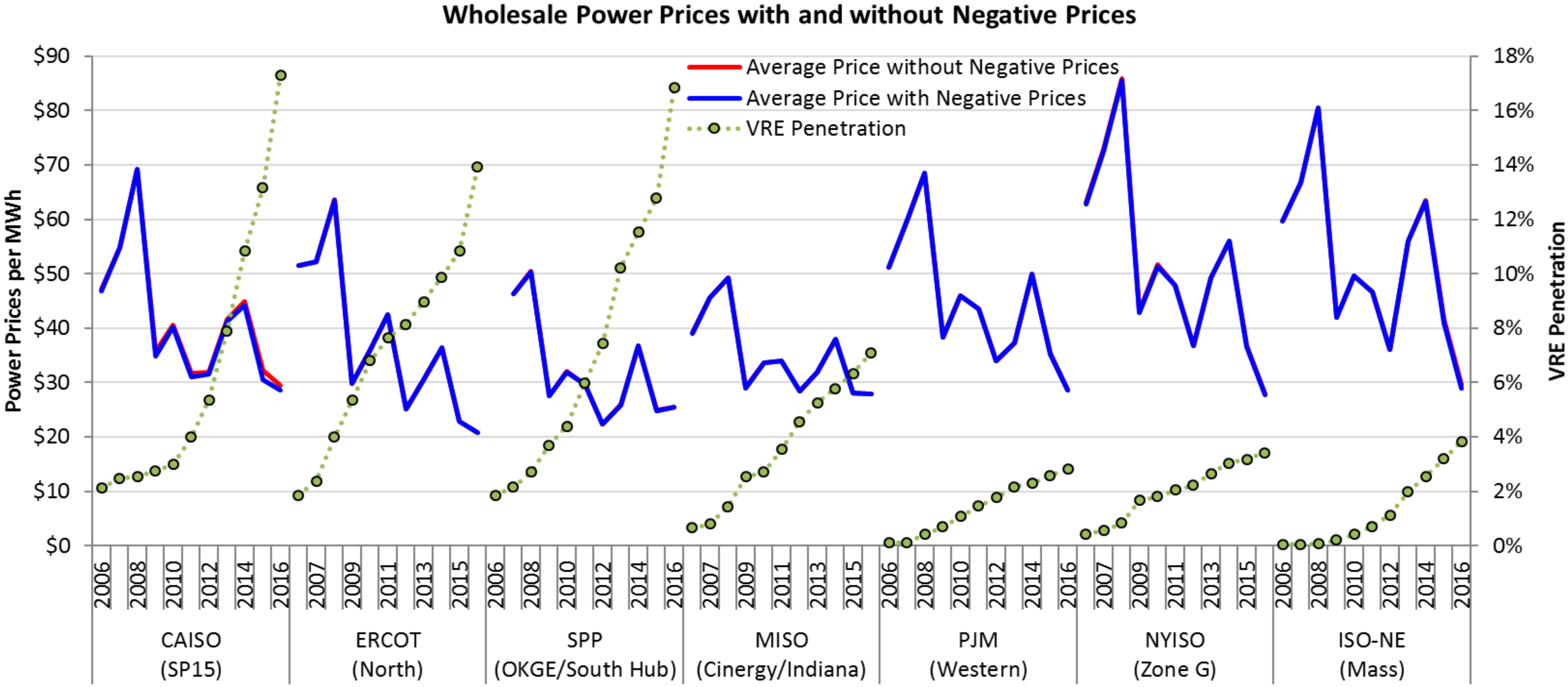




Focuses on selected major trading hubs

Negative Prices Have Had Little Impact on Avg. Prices Outside CAISO, for these Specific Hubs

Among these hubs, a noticeable effect is only apparent in CAISO, where RT wholesale prices in 2015 were $1.7/MWh (6%) lower due to negative prices. This gap equals $0.9/MWh (3%) in 2016.



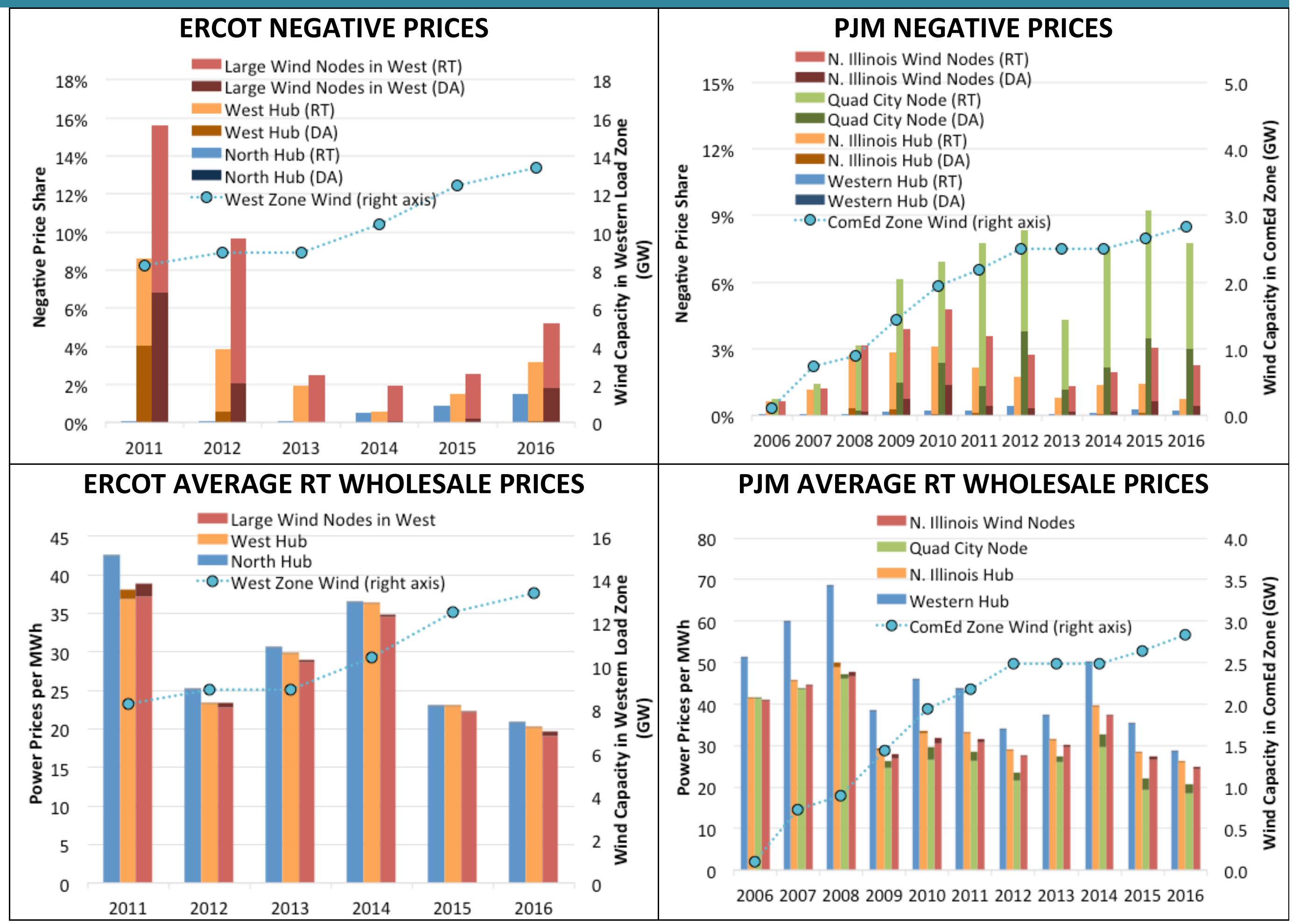
Average without Negative Prices replaces negative prices with $0/MWh prices; Focuses on selected major trading hubs

Larger Impacts In Constrained Pricing Zones: Focus on West Texas and Northern Illinois

Major trading hubs do not reveal the full story. Transmission limits between where generation is located and load centers can lead to congestion and a higher prevalence of negative prices.

Negative prices more common in W. Texas and Quad City

Average annual prices also lower in constrained zones



Note: Average real-time prices without negative prices are shown as the dark band on top of the average wholesale prices with negative prices.

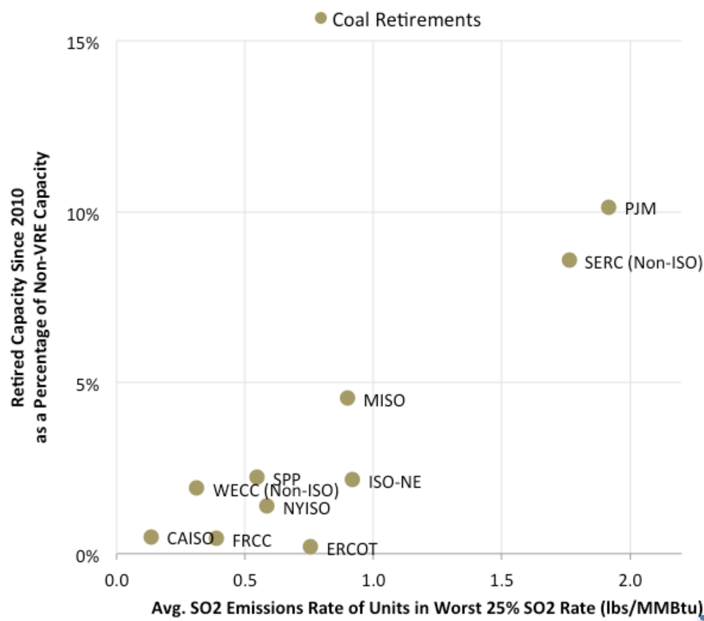
Thermal Plant Retirement Drivers Are Diverse

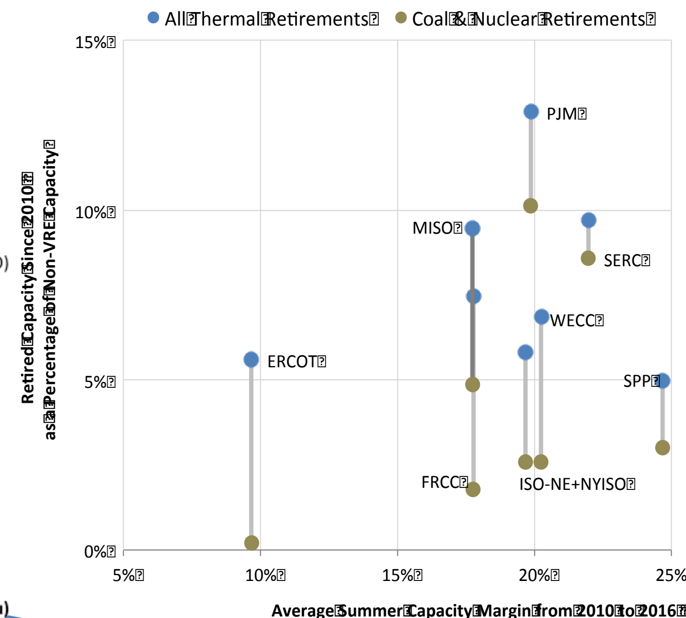
Variations in recent (2010-2016) regional thermal plant retirement percentages correlated with nine possible drivers

- VRE penetration in percentage terms, considering utility-scale wind and PV and distributed PV
- Regional growth (or contraction) in electrical load from 2010 to 2016
- Average planning reserve margin (based on summer capacity and peak loads) from 2010 to 2016
- Average SO_2 emissions rates of the 25% of coal plants in each region with the highest emissions
- Average percent sulfur content of coal delivered to the region from 2010 to 2015
- Ratio of delivered coal prices to delivered gas prices in the region from 2010 to 2016
- Average regional delivered natural gas price from 2010 to 2016
- Average age of the oldest 25% of thermal power plants in the region in 2010
- New non-VRE capacity additions since 2010 as a percentage of total non-VRE capacity

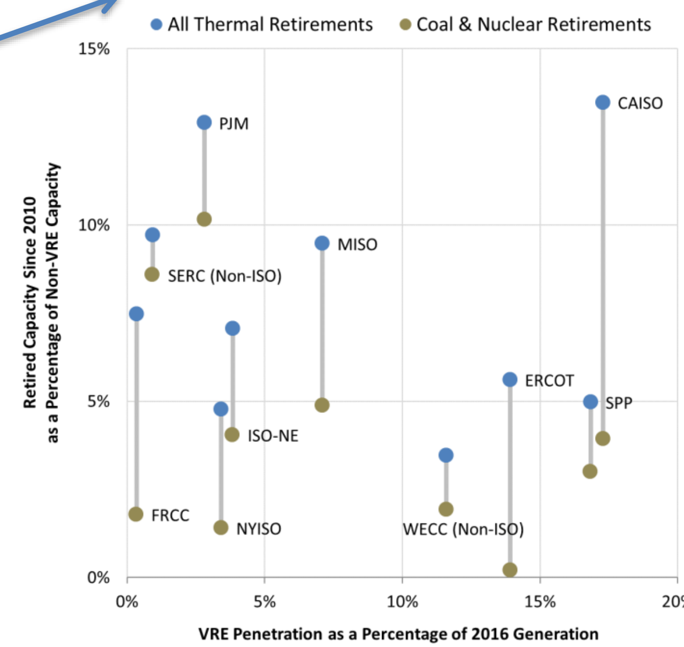
VRE Has Not Played Major Role Historically; Is a Contributor for Some Specific Plants

Based on correlations, the strongest predictors of regional retirement variations include SO_2 emissions rates, planning reserve margins, variations in load growth or contraction, and the age of older thermal plants. Additional apparent predictors include the ratio of coal to gas prices and delivered natural gas prices. Other factors appear to play lesser roles: VRE penetration, recent non-VRE additions, and whether the region hosts an ISO or remains regulated.





Stronger predictors of retirements



Weaker predictor of retirements

Prospective Future Impacts of VRE on the Bulk Power System

Chapter Content

Building on the anticipated directional impacts and the historical observed impacts, in this chapter we review selected U.S.-based literature that models prospective future impacts of high VRE

Selected studies take one of two approaches

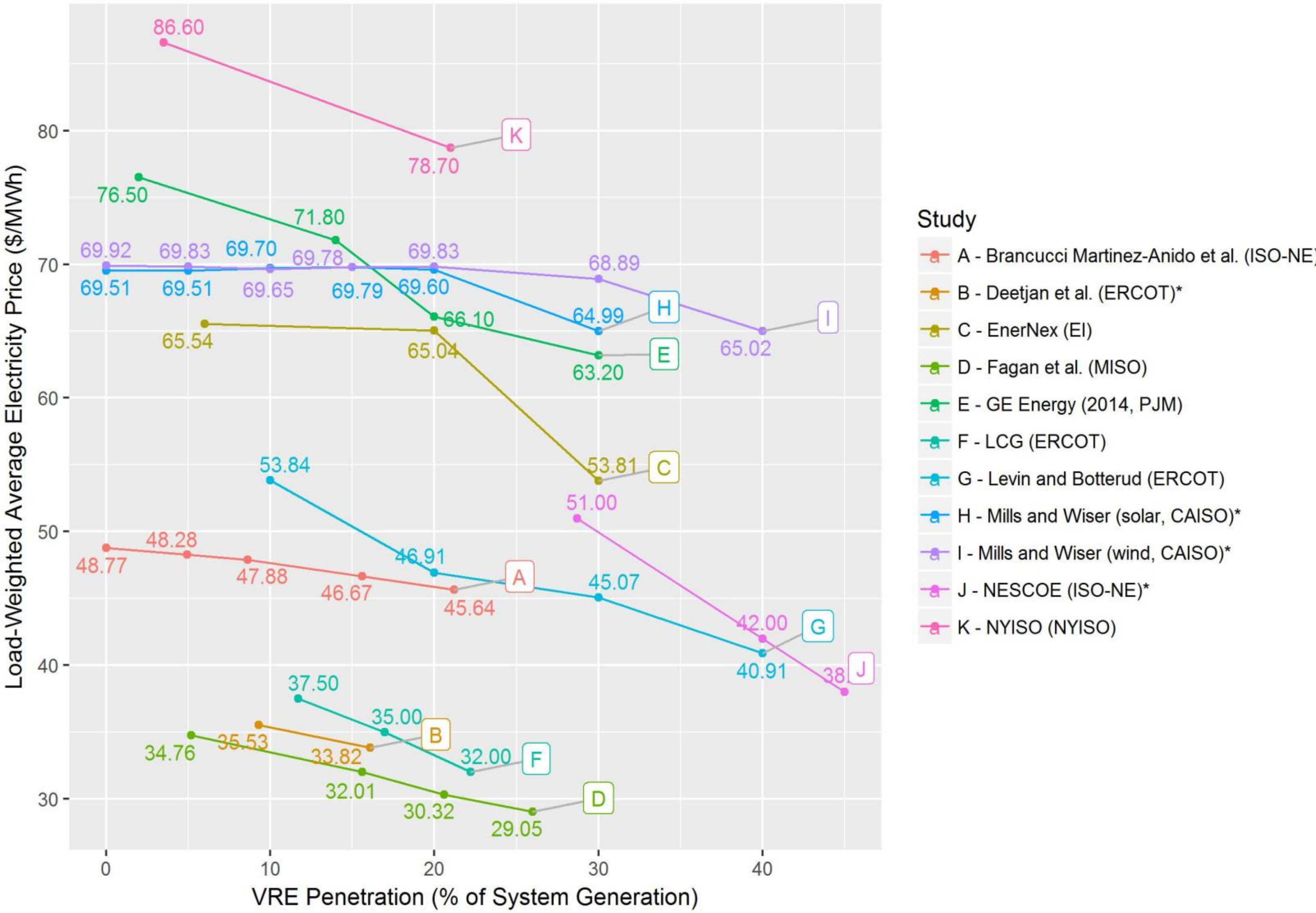
- Fix capacity of the existing generation fleet irrespective of the introduction of new VRE
- Define investment and retirement of thermal units for each scenario of VRE capacity

Many additional caveats apply to this review

- Selective study selection, certainly not fully comprehensive
- Generally presume competitive wholesale electricity markets, with simplified modeling
- Different timeframes, approaches, models, resolution, regions, and assumptions
- Not appropriate to make direct comparisons across different studies and regions
- Most studies focus on short- to medium- term impacts; fewer long-term equilibrium
- Most studies explored aggressive VRE penetration levels—well above current levels

Directions for future research

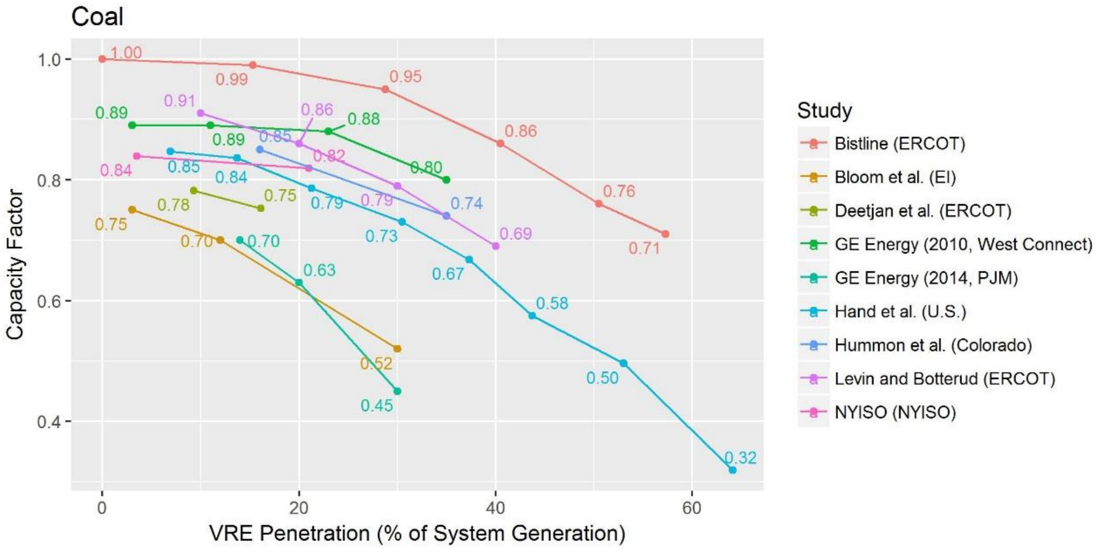
VRE Decreases Average Wholesale Prices in the Short Run; Less Pronounced in Long Run

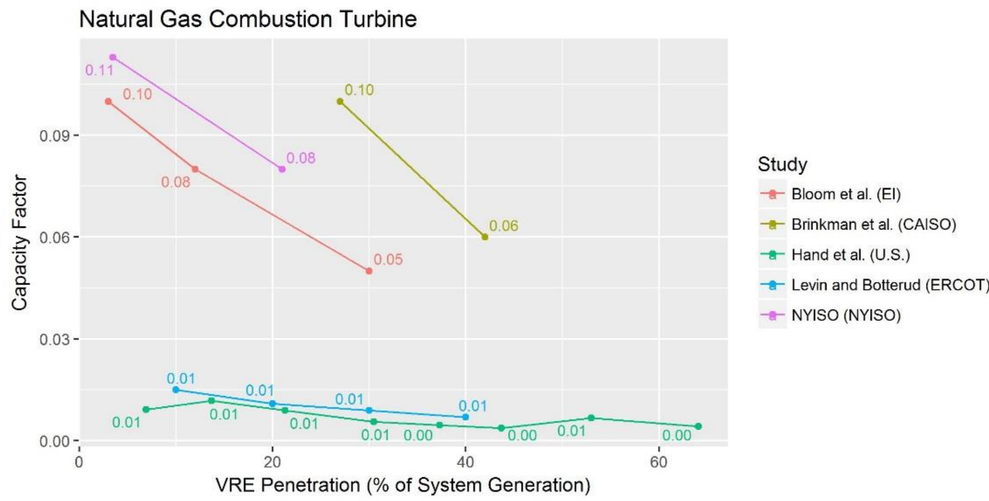


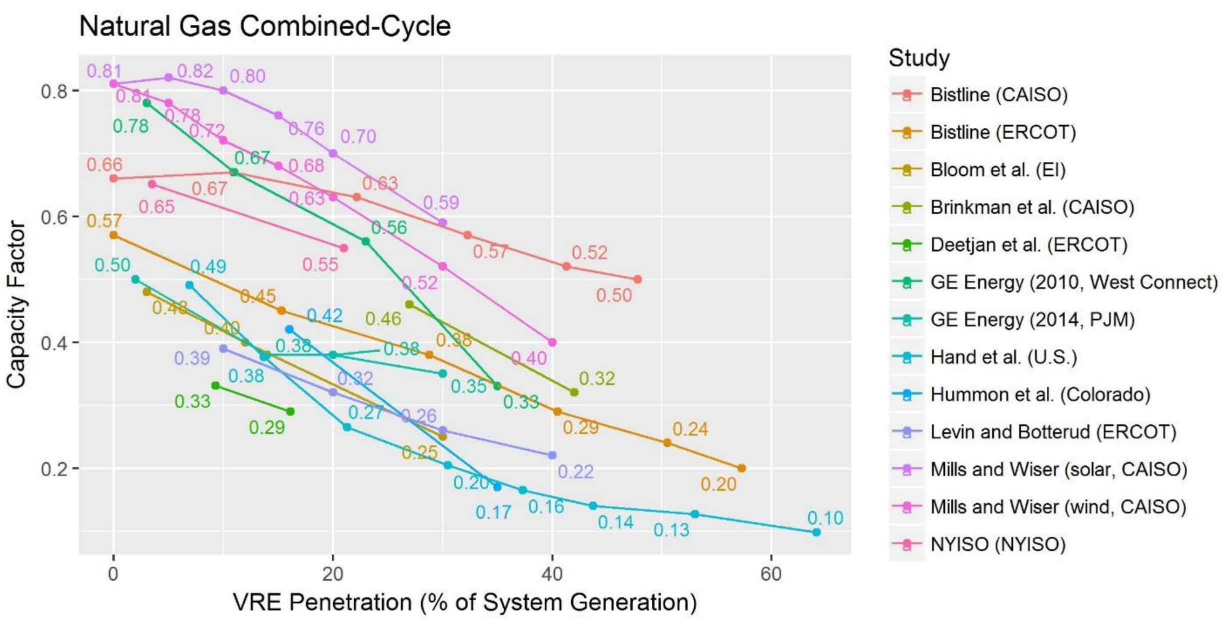
Many studies do not reflect equilibrium conditions; in the long run, price impacts expected to be less pronounced due to changes in the generation mix as that mix adapts to higher levels of VRE

Systems with high penetrations of other low marginal cost resources—e.g. nuclear—would experience similar dynamics

VRE Impacts Capacity Factors of Thermal Power Plants

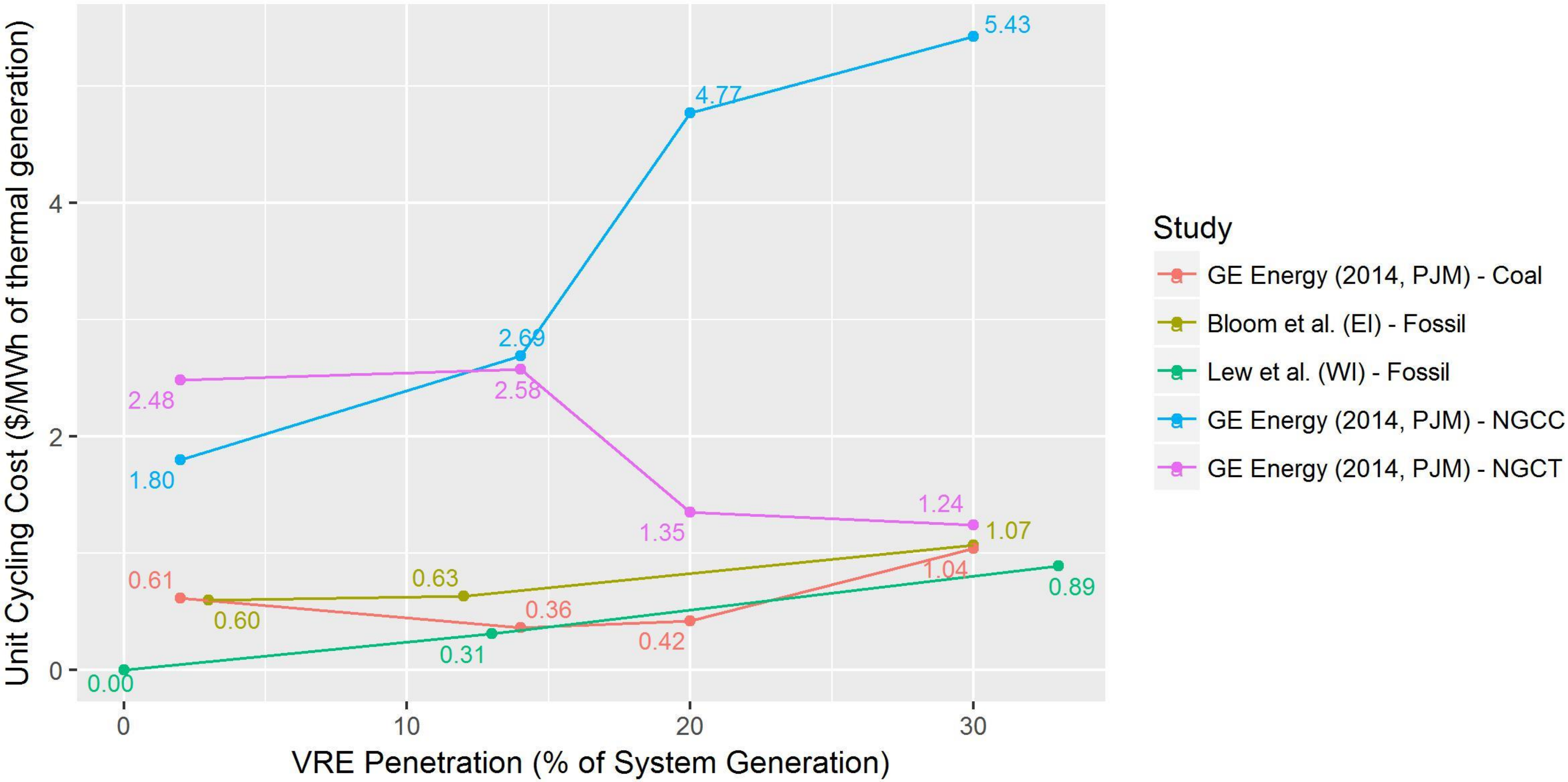






Capacity factors tend to decrease for thermal units with increasing VRE. Nuclear units are typically modeled as inflexible baseload generation, in which case capacity factors are not influenced by VRE.

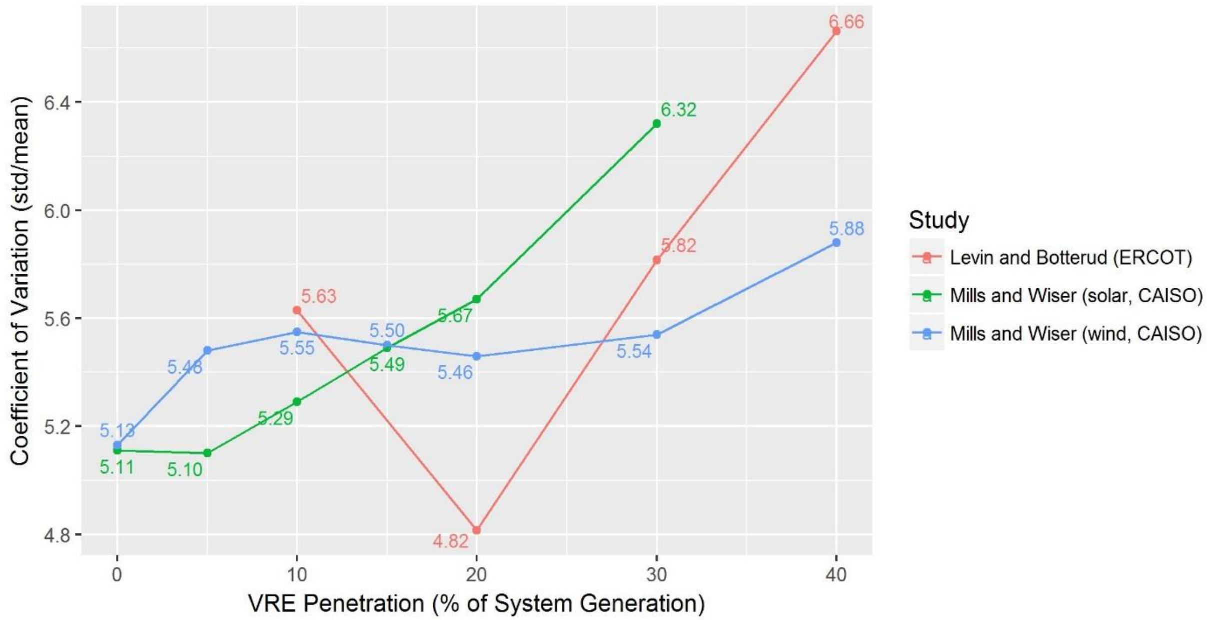
VRE Impacts Cycling of Thermal Power Plants



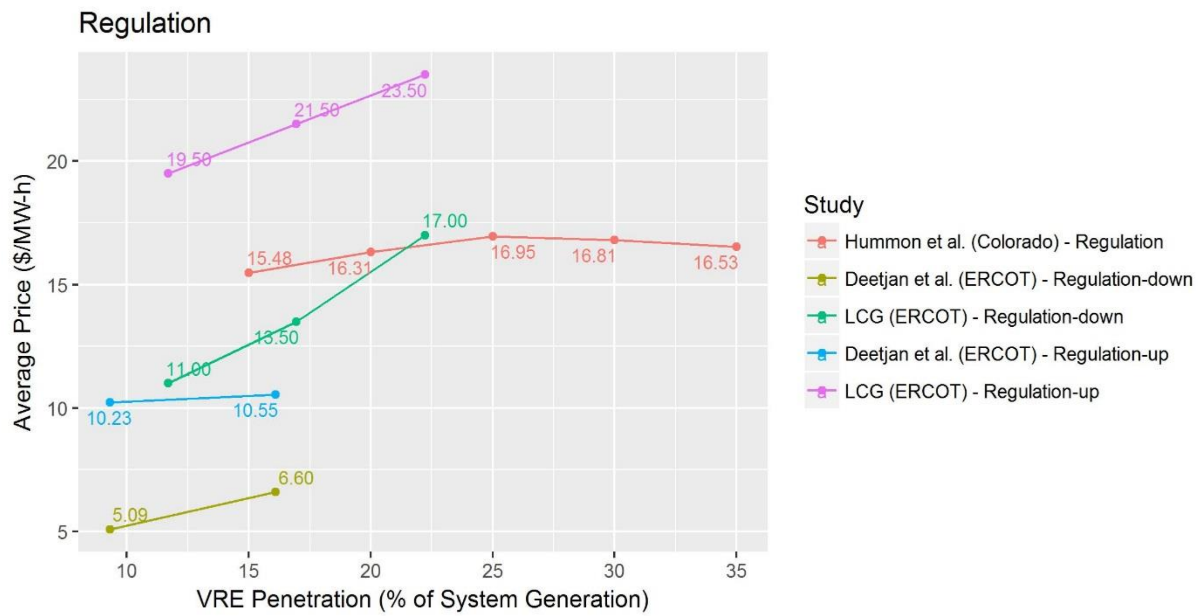
Coal cycling costs appear to increase at higher VRE, but results may be unit- or technology-specific and it is difficult to broadly generalize. Some studies have found that cycling costs of CTs are lower at higher VRE penetrations.

VRE Creates Signals for Increased Flexibility

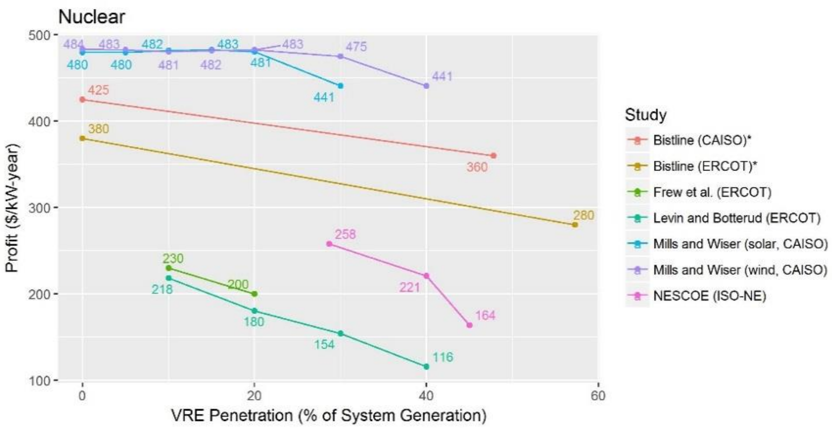
VRE May Increase Price Variability

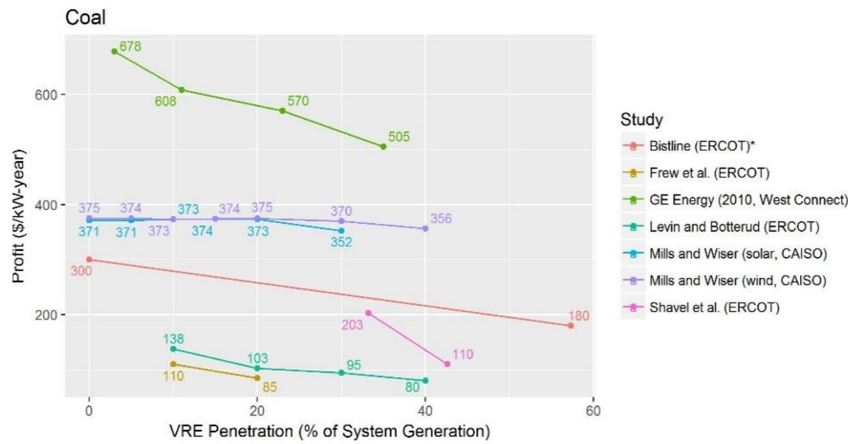


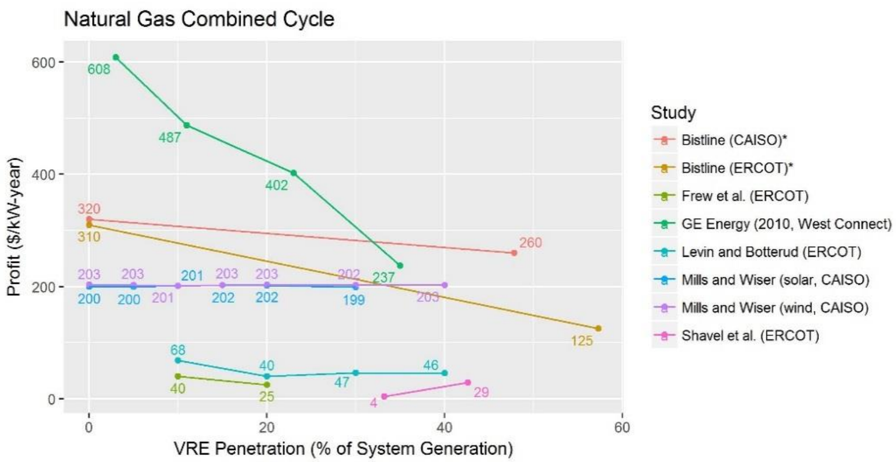
VRE May Impact Operating Reserve Prices

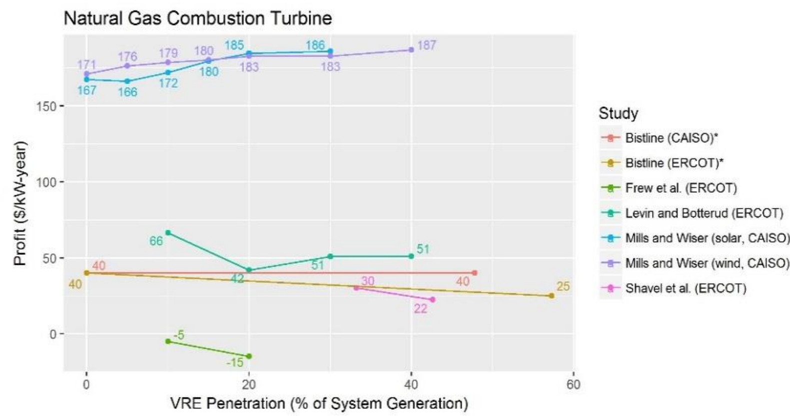


VRE Reduces Revenue & Operating Profits of Nuclear & Coal; Flexible Gas Less Exposed









Nuclear & coal profits / revenues generally decrease with VRE; magnitude differs based in part on whether longer-term equilibrium solutions are explored

- Operating profits of gas fired generators are less exposed to increasing VRE levels given their flexibility characteristics
- Few studies comprehensively included possible revenues from capacity and AS markets, making comparisons difficult

System Value and System Costs of Variable Renewable Energy

Chapter Content

LCOE is an imperfect measure of the relative economics of generation resources: introduce and synthesize literature on the “system value” and “system cost” of VRE (and other resources)

Ideally, invest up to point where LCOE = “system value”

- System value includes energy, capacity, balancing, and transmission considerations
- Narrow definition used here focused on avoidable direct costs; not limited to VRE
- Acknowledge other societal values that often drive policy: diversity, environmental, etc.
- “Market value” sometimes different from “system value” as not all values are priced

Alternatively, “system cost” sometimes introduced as adder to LCOE

- All technologies have system costs, not limited to only VRE
- A controversial and complicated area of research and application
- Challenging to account for all relevant differences in simplified framework

Directions for future research

System Value of VRE Varies by Technology and Location, Changes with VRE Penetration

- System value of PV often exceeds that of flat-block at low penetration
- As penetrations increase, value of PV declines rapidly
- System value of wind is lower than PV at low penetrations
- As penetrations increase, system value of wind declines, but at slower rate than PV
- Multiple options to slow declining system value of VRE

Literature not always inclusive of all values

(a)

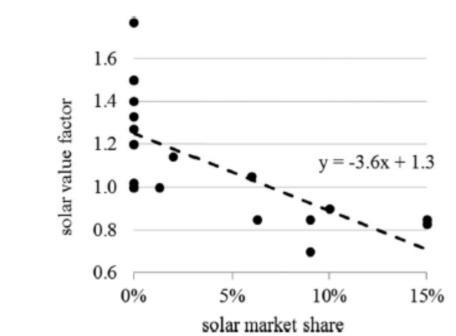


Fig. 6 *Solar market value literature. OLS-fit of all studie estimates the solar value factor to fall from 1.3 at zero penetratio to 0.7 at 15% penetration*

Source: Hirth, Ueckerdt, and Edenhofer (2015)

(b)

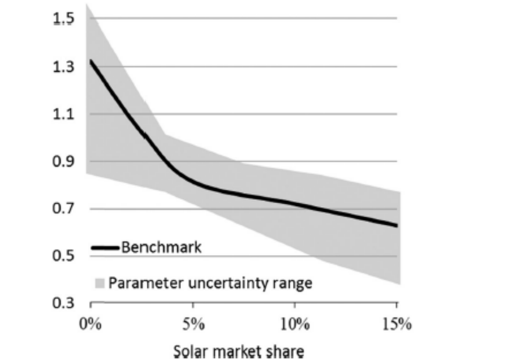
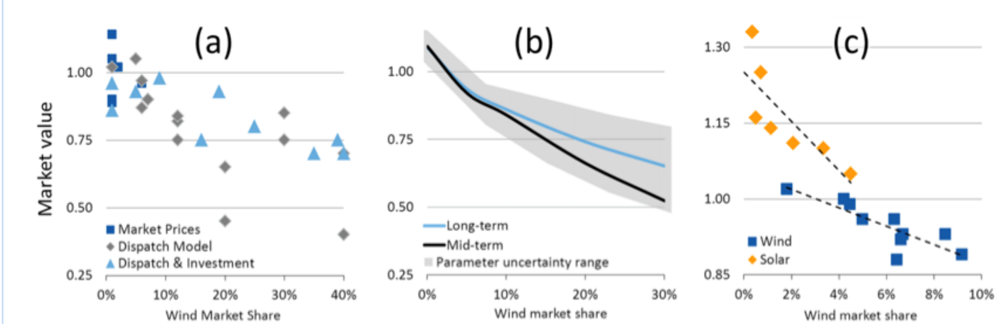


Fig. 14 *Long-term solar value factor drops to 0.4–0.8 at 15% penetration rate*

Source: Hirth, Ueckerdt, and Edenhofer (2015)

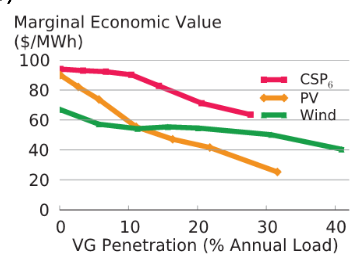
(c)



Wind value factor estimates from a literature review (a), the numerical model EMMA (b), and German historical market data (c). The value factor (wind revenue over base price) decreases with higher penetration rates.

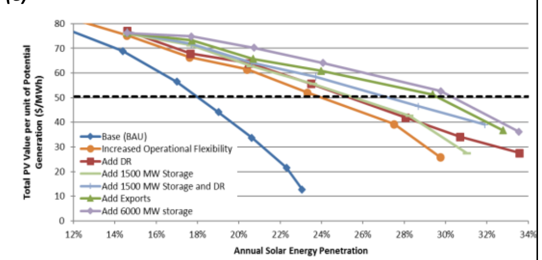
Source: Hirth (2013)

(d)



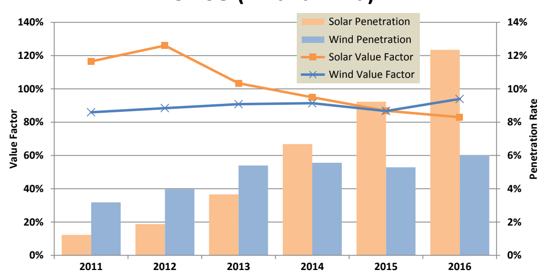
Source: Mills and Wiser (2012)

(e)



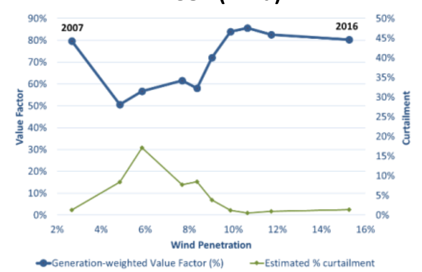
Source: Denholm et al. (2016)

CAISO (PV and wind)



Source: LBNL analysis

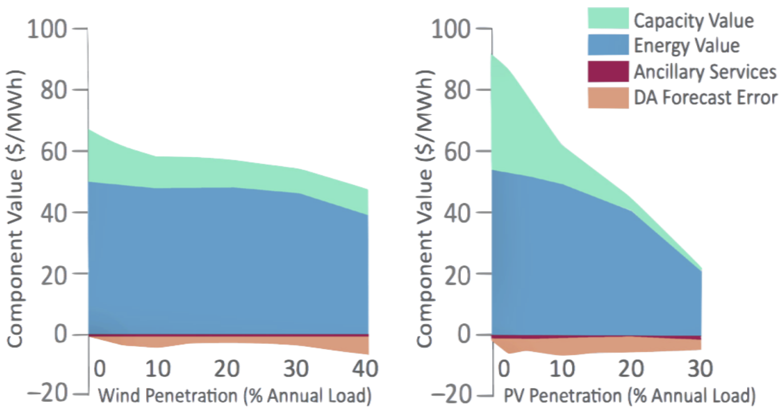
ERCOT (wind)

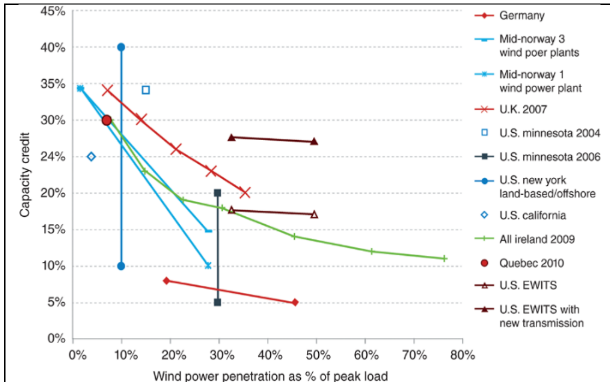


Source: LBNL analysis

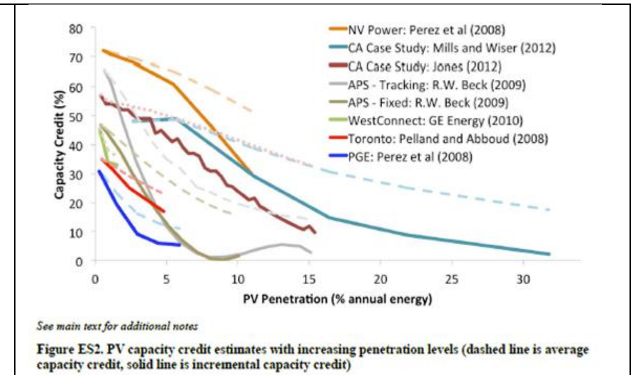
System Value Is Impacted by Energy, Capacity, Balancing, and Transmission

Most literature has focused on VRE, but impacts are not restricted to VRE

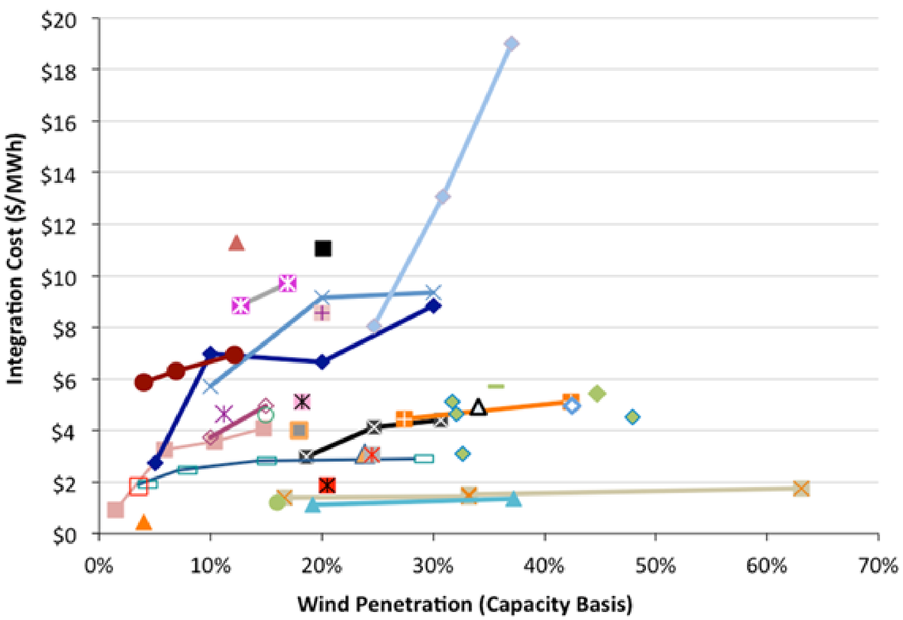




Source: Milligan et al. (2017)



Source: Mills and Wiser (2012b)



Study	Wind Penetration Level Low	Wind Penetration Level High	Notes
Survey of transmission planning studies in the U.S. (Mills, Wiser, and Porter 2012)	$15/MWh		Extremely wide cost range in individual studies; estimate based on median study
Western Wind and Solar Integration Study (GE Energy 2010b)	$0/MWh	$18/MWh	Low penetration and local development of wind requires no additional transmission; high penetration and geographically concentrated wind requires more transmission
Eastern Wind Integration and Transmission Study (EnerNex Corp. 2010)		$10-20/MWh	Lower transmission cost associated with lots of offshore wind; higher transmission cost for scenario with all onshore wind
ERCOT CREZ (RS&H 2011)		$29/MWh	October 2011 estimate of CREZ transmission costs; actual costs ended up higher[1]
20% Wind Energy by 2030 Study (DOE 2008)		$10/MWh	Transmission expansion based on ReEDS model; 25% of wind did not require new transmission investment
Wind Vision: A New Era of Wind Power in the United States (DOE 2015)		$5/MWh	Transmission expansion based on ReEDS model
Analysis of Western Renewable Energy Zones (Mills, Phadke, and Wiser 2011)	$20/MWh	$25/MWh	Includes estimate of cost of losses, and assumes that all existing transmission is fully utilized and that new transmission cost is fully assigned to wind; does not consider 'local' wind

"System Costs" Of VRE: An Alternative to the System Value Perspective

- Policymakers sometimes seek to avoid sophisticated models that capture cost and system value differences
- Given the limits of LCOE, some research has involved the creation of adjustments to the LCOE of wind and PV to account for the so called "system costs" of VRE
- Can compare resources based on LCOE + system cost, but need to estimate system cost for all resource options and avoid double counting
- Two methods for assessing system cost in the literature:
  - Difference between system value of a resource relative to a flat block
  - Separate calculation of energy, capacity, balancing, transmission cost
- Given complexities, decision-makers typically use models, do not consider "system costs" as separately identifiable

System Cost Estimates for VRE Span a Wide Range, Depend on Myriad of Factors

Estimating 'System Costs' from Value Factor Estimates

- **Solar:** ~ **-**10/MWh at low penetration, **+**$10-30 at 15% penetration, and **+**$30 at 30% penetration
- **Wind:** ~ **+**$5/MWh at low penetration, **+**$5-15 at 15% penetration, and **+**$7.5-25 at 30% penetration
- Transmission, not fully considered above, might represent a negative system cost for some PV located near load to an additional system cost of ~$15/MWh or more for remote VRE

Estimating 'System Costs' from Underlying Drivers

- IPCC: $7-30/MWh for wind up to 20%
- Hirth et al: $27-38/MWh for wind at 30-40%
- IEA: $17/MWh for VRE in 2035
- Agora: $6-22/MWh for 50% VRE
- Scholz et al: $13-30/MWh for VRE growing from 20% to 100%

Conclusions

Summary of Findings

All generation types are unique in some respect, and wholesale markets, industry investments, and operational procedures have evolved to manage the characteristics of a changing generation fleet. With increased VRE, power system planners, operators, regulators, and policymakers will continue to be challenged to develop methods to smoothly and cost-effectively manage the reliable integration of these new sources of electricity supply.

- VRE is already impacting the bulk power market
- VRE impacts on average wholesale prices have been modest
- VRE impacts on power plant retirements have so far been limited
- VRE impacts on the bulk power market will grow with penetration
- The 'system value' of VRE will decline with penetration
- Power system flexibility can reduce the rate of VRE value decline

Future Work that Builds on this Foundation

Additional Proposed Research Will Build on This Foundation

- Supply Curve Extensions
  - Refine analysis of CAISO and ERCOT
  - Apply to other ISO regions where data is available
  - Peek-forward over next 5 years or so
- Statistical assessments of historical pricing
  - Led by NREL; LBNL in an advisory role
  - Summary paper to bring complementary LBNL & NREL work together
- Impact of VRE on historical price variability
  - Extend analysis of pricing impacts at particular locations
  - Extend analysis of impacts on temporal patterns in pricing