Variable Renewable Energy Participation in U.S. Ancillary Services Markets: Economic Evaluation and Key Issues

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Sep 2021

This work was funded by the U.S. Department of Energy Office of Energy Efficiency and Renewable Energy, under Contract No. DE-AC02-05CH11231.

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Introduction

- Rising penetrations of variable renewable energy (VRE) are reducing VRE energy and capacity value in organized markets; VRE owners are looking for other sources of value
- Rising VRE penetrations are also creating new challenges for system operations; system operators will need to explore low-cost integration solutions
- Enabling VRE participation in AS markets could provide additional revenue sources and allow system operators to access lower-cost integration solutions

Two main study questions:
1) What is the incremental value ($/MWh) of AS market participation to standalone and hybrid* VRE resource owners?
2) What is the value ($/MW-hr) of AS market participation to system operators?

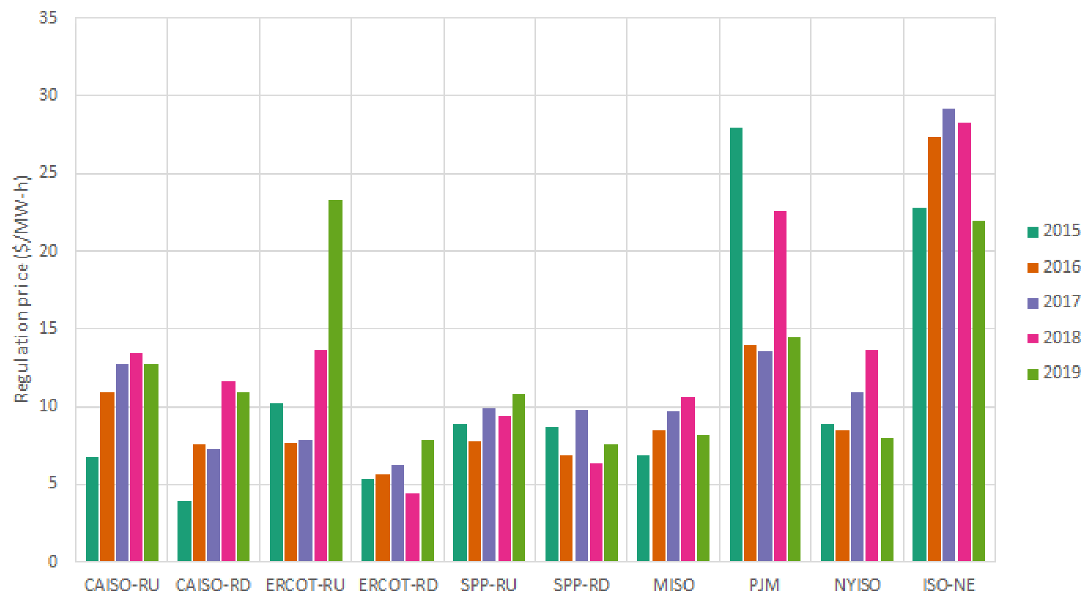
Three secondary study questions:
1) What are the barriers to VRE participation in AS markets?
2) How might the value of VRE participation in AS markets change with higher VRE penetrations?
3) What other services might VRE provide in the future?

** Hybrid refers to VRE with co-located storage*

Background: ISO/RTO AS markets

- ISO/RTO AS markets have significantly different products, procurement practices, and price formation
  - Design differences have significant impact on AS prices, price structure, and value
- AS prices vary significantly year to year
  - Price variance driven by fuel costs, loads, hydro variability, market design changes

Simple average zonal regulation prices used in this analysis by ISO/RTO, 2015-2019



Notes: RU refers to regulation up, RD refers to regulation down
Source: Prices are from Velocity Suite

Background: ISO/RTO AS markets

- Three differences in ISO/RTO AS market design that are most relevant for this analysis:
  - **Products**: separate regulation up/down (CAISO, ERCOT, SPP) or bidirectional regulation (ISO-NE, MISO, NYISO, PJM)
  - **Co-optimization**: day-ahead and real-time co-optimization (CAISO, MISO, NYISO, SPP), real-time co-optimization (ISO-NE, PJM), day-ahead co-optimization (ERCOT); differences in which reserves are co-optimized
  - **Price cascading**: regulation ≥ spinning ≥ non-spinning/supplemental (CAISO, MISO, NYISO, SPP) or spinning ≥ non-spinning (ERCOT, ISO-NE, PJM)
- For overviews of ISO/RTO AS markets, see Ellison et al. (2012), Zhou et al. (2016), and Ela et al. (2019)

Background: VRE participation in AS markets

- Standalone VRE's ability to provide essential reliability services has been extensively demonstrated (Kirby and Milligan, 2009; Ela et al., 2014; Milligan et al., 2015; Loutan et al., 2017; Rebello et al., 2020) but limited participation in U.S. AS markets to date
- ISOs/RTOs beginning to address hybrid VRE participation models after FERC Order 841; CAISO's hybrid participation model became operational in December 2020, allows AS provision
- Standalone and hybrid VRE participation in AS markets would have different operations and economics

Background: Standalone VRE participation

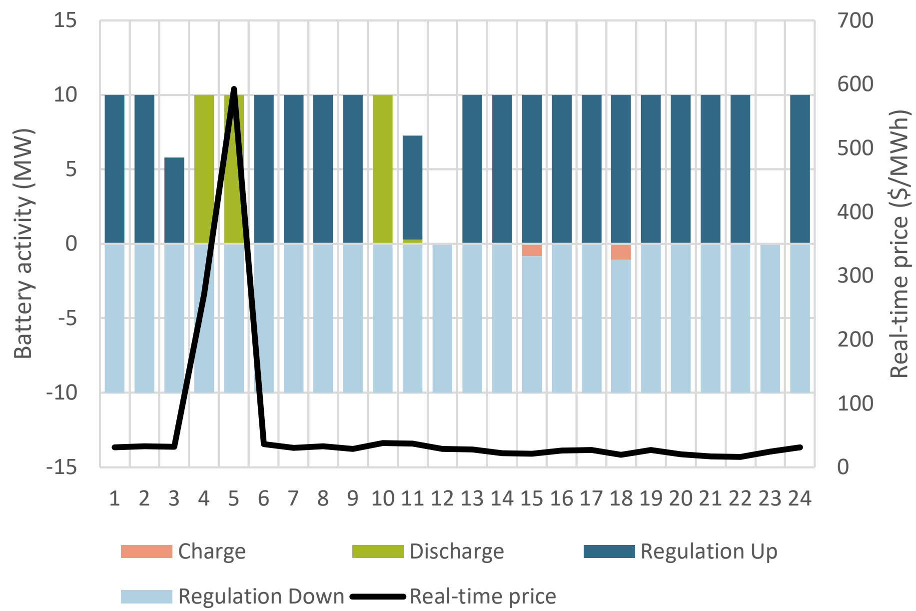
- Standalone VRE provision of different reserves/products would have different operating requirements and economic principles

	Upward reserve (regulation up, spinning)	Downward reserve (regulation down)	Bidirectional regulation
Day-ahead market operations	Reduction in day-ahead forecasted output (financial) during scheduling interval	No changes to day-ahead forecasted output	Reduction in day-ahead forecasted output (financial) during scheduling interval
Real-time market operations	Curtailment of 5-minute forecast in target dispatch interval	No curtailment of 5-minute forecast	Curtailment of 5-minute forecast in target dispatch interval
Reserve dispatch	Upward regulation energy and contingency dispatch	Curtailment (downward regulation)	Upward/downward regulation energy
Opportunity cost	Cost of not providing energy (LMP), minus any revenues from reserve dispatch	Cost of not providing energy (LMP) when curtailed for regulation energy	Cost of not providing energy (LMP)
Energy versus reserve provision	Provide reserves if reserve price + energy revenues > energy price	Provide reserves if reserve price > lost revenues from regulation down energy	Provide reserves if reserve price > energy price

Background: Hybrid VRE participation

- In hybrid VRE, storage will dominate reserve provision
- Batteries tend to maintain state of charge (SOC) sufficient to provide downward regulation at max charge rate and then provide upward regulation, unless (a) energy price differences are high enough to offset lost regulation revenues during time between energy charge and discharge or (b) regulation prices are low

Illustration of battery dispatch on a day with an energy price spike



- Point of interconnection (POI) capacity limits may limit total output from VRE + storage facility
  - POI capacity may be less than nameplate VRE capacity + storage discharge capacity

Analysis methods

- 20 MW wind and solar facilities (standalone and hybrid), 10 MW/40 MWh battery storage (hybrid)
- Profit maximizing dispatch against 2015-2019 ISO/RTO energy and reserve prices
  - Real-time energy, regulation, and spin prices in all markets except for ERCOT; day-ahead prices in ERCOT
- Base case only includes regulation reserves
  - Regulation up/down (CAISO, ERCOT, SPP), bidirectional regulation (ISO-NE, MISO, NYISO, PJM)
  - Spinning reserve provision considered as a sensitivity

Metrics

Resource owner value $$\Delta r = \frac{NE_1 + AS_1 - NE_0}{G_{PC}}$$

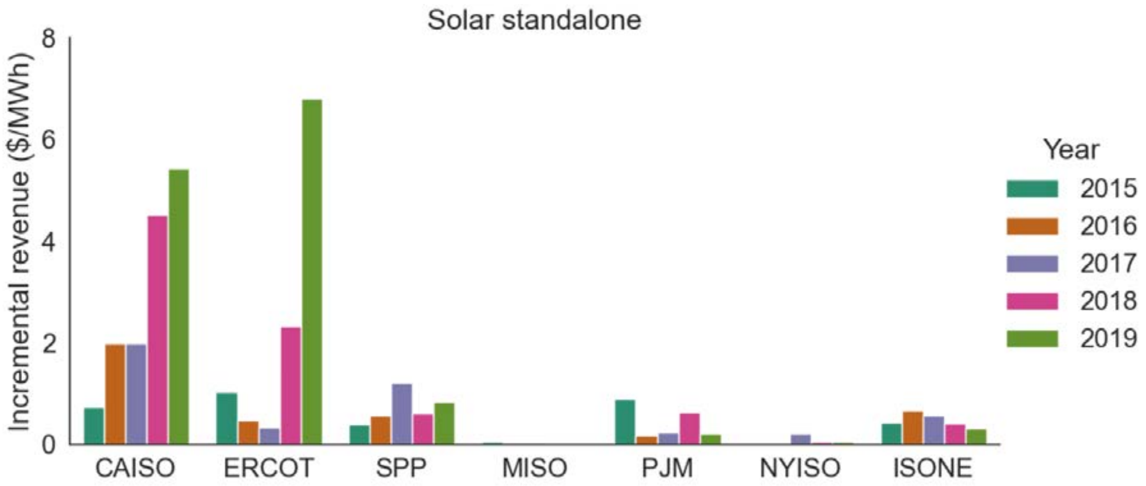
ISO value $$v = \frac{AS_1}{RS_1}$$

r = unit revenue, pre-curtailment MWh ($/$MWh_{PC}$)
NE = net energy revenue ($/yr)
AS = reserve revenue ($/yr)
G_{PC} = pre-curtailment VRE generation (MWh_{PC}/yr)
v = unit AS value ($/MW-h)
RS = AS provision (MW-h/yr)
Subscript 1 = with AS case
Subscript 0 = without AS case
Subscript PC = pre-curtailment

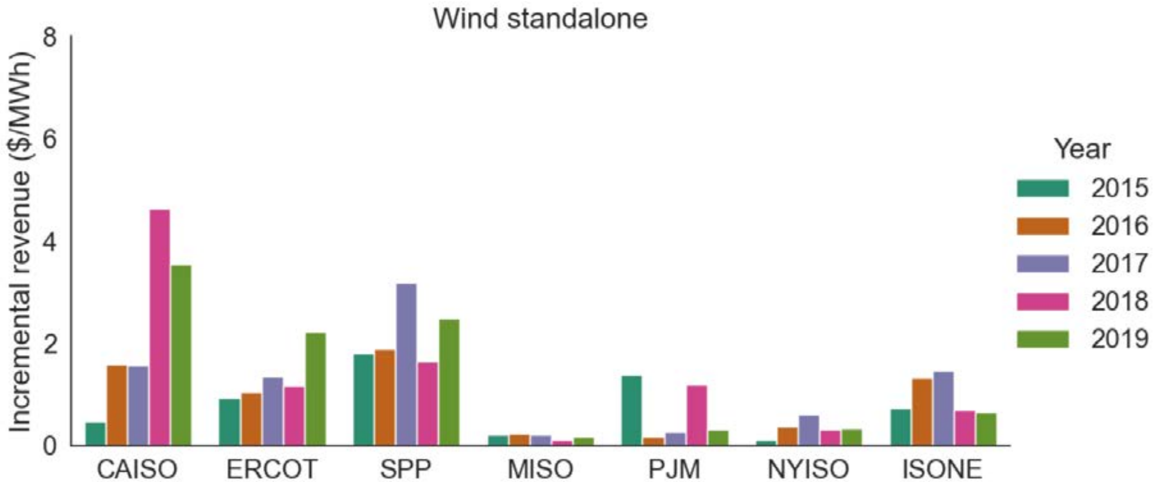
Analysis methods

- Other key assumptions:
  - Zonal AS prices, chosen using “central plant” search algorithm
  - POI capacity limited to 20 MW (VRE facility nameplate capacity), maximum POI capacity of 30 MW (VRE + battery capacity) considered as a sensitivity
  - For hybrid VRE, only battery can provide reserves (assuming storage reserve value >> VRE reserve value)
  - Regulation reserves provide energy (up/down) equivalent to 30% of regulation award, spinning reserves provide contingency dispatch energy equivalent to 2% of spinning award
  - Deterministic hourly resource profile for wind and solar, perfect foresight for battery dispatch
  - For standalone VRE, wind and solar can provide reserves equivalent to 20% of hourly profile, minimum of 1 MW
  - Different battery degradation rates for energy ($5/MWh) and reserves ($25/MWh for dispatched energy)
  - Battery SOC not limited by contractual requirements (e.g., RA requirements)
  - Analysis does not consider mileage value (expected to be low relative to AS capacity value and opportunity cost)

Results: Incremental value for standalone VRE owner



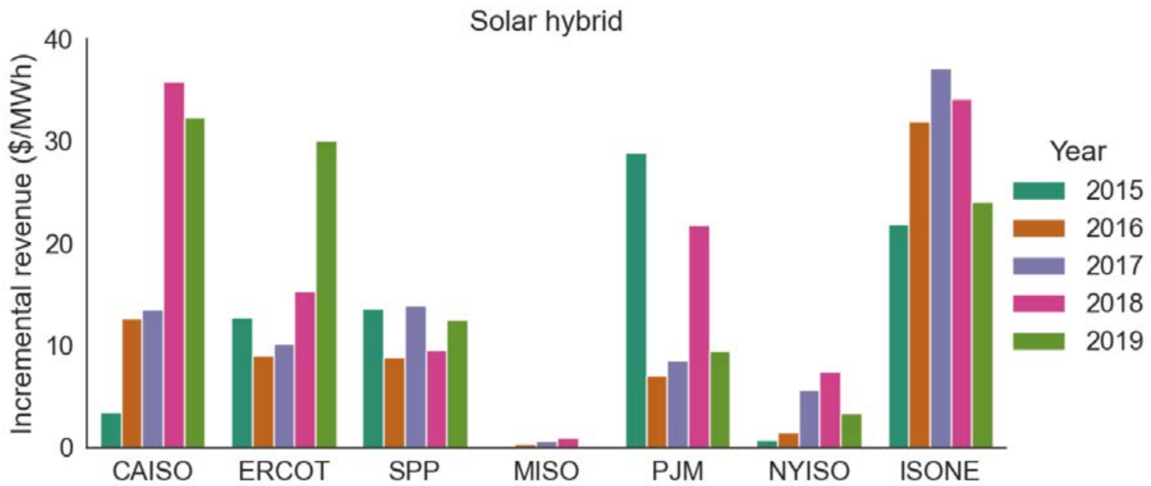
Averages (%Δ)	$2.9/MWh (10%)	$2.2/MWh (6%)	$0.7/MWh (3%)	$0.0/MWh (0%)	$0.4/MWh (1%)	$0.1/MWh (0%)	$0.5/MWh (1%)



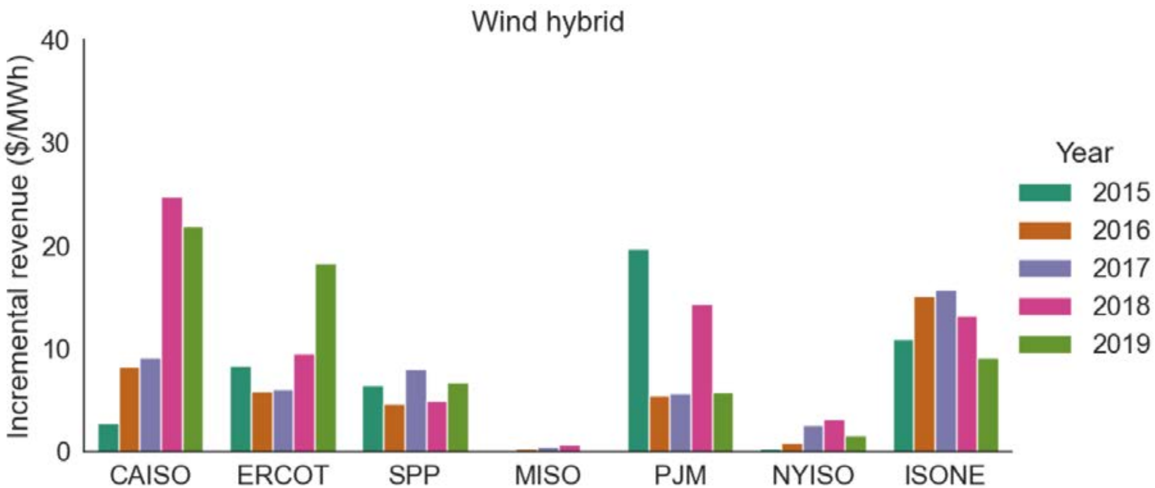
Averages (%Δ)	$2.4/MWh (7%)	$1.3/MWh (7%)	$2.2/MWh (15%)	$0.2/MWh (1%)	$0.7/MWh (2%)	$0.4/MWh (1%)	$1.0/MWh (3%)

- Low to medium average incremental (Δ $/MWh$_{PC}$) value in most markets; higher in some ISOs/RTOs and high in some years
- Differences in value among ISOs/RTOs due in part to market design
  - Separate regulation up/down versus bidirectional regulation
- Inter-annual value differences within ISOs/RTOs driven by prices and energy-regulation price relationship
- Differences in solar versus wind driven by differences in profiles and capacity factors

Results: Incremental value for hybrid VRE owner



	CAISO	ERCOT	SPP	MISO	PJM	NYISO	ISONE
Averages (%Δ)	**$20/MWh (47%)**	**$15/MWh (37%)**	**$12/MWh (34%)**	**$0.5/MWh (1%)**	**$15/MWh (33%)**	**$4/MWh (8%)**	**$30/MWh (62%)**



	CAISO	ERCOT	SPP	MISO	PJM	NYISO	ISONE
Averages (%Δ)	**$13/MWh (33%)**	**$10/MWh (38%)**	**$6/MWh (32%)**	**$0.3MWh (1%)**	**$10/MWh (31%)**	**$2/MWh (6%)**	**$13/MWh (31%)**

- Average incremental (Δ $/MWh$_{PC}$) value much higher than hybrids than for standalone
- Differences in value among ISOs/RTOs and years mainly driven by differences in regulation price levels and energy price variance
- Differences in solar versus wind driven by differences in profiles, capacity factors, and timing of POI capacity constraints

Results: Value for system operator

Regulation provision and regulation value to ISOs/RTOs, 2018 prices

		Regulation provision (average MW), % capacity in parentheses				Regulation value and ISO average regulation price ($/MW-h)				
		Standalone		Hybrid		Standalone		Hybrid		ISO
		Solar	Wind	Solar	Wind	Solar	Wind	Solar	Wind	AVG
CAISO	**RD**	0.95 (5%)	0.91 (5%)	4.37 (44%)	4.23 (42%)	$26	$31	$31	$32	$12
	RU	0.42 (2%)	0.47 (2%)	3.92 (39%)	3.54 (35%)	$37	$62	$38	$40	$14
	Total	1.37 (7%)	1.38 (7%)	8.29 (83%)	7.78 (78%)	$29	$42	$34	$36	
ERCOT	**RD**	0.18 (1%)	0.82 (4%)	1.49 (15%)	1.45 (14%)	$8	$11	$14	$15	$4
	RU	0.24 (1%)	0.54 (3%)	3.09 (31%)	3.10 (31%)	$78	$16	$32	$32	$14
	Total	0.42 (2%)	1.36 (7%)	4.58 (46%)	4.55 (45%)	$48	$13	$26	$27	
SPP	**RD**	0.28 (1%)	1.32 (7%)	2.73 (27%)	2.42 (24%)	$12	$13	$15	$16	$9
	RU	0.15 (1%)	0.70 (3%)	2.43 (24%)	2.20 (22%)	$34	$14	$22	$23	$6
	Total	0.43 (2%)	2.02 (10%)	5.16 (52%)	4.63 (46%)	$19	$13	$18	$19	
MISO		0.03 (0%)	0.28 (1%)	1.22 (12%)	1.33 (13%)	$7	$6	$12	$12	$11
PJM		0.11 (1%)	0.27 (1%)	6.15 (62%)	6.00 (60%)	$67	$64	$26	$27	$23
NYISO		0.04 (0%)	0.38 (2%)	3.79 (38%)	3.05 (30%)	$10	$11	$15	$15	$14
ISO-NE		0.16 (1%)	0.51 (3%)	10.19 (102%)	8.26 (83%)	$34	$32	$21	$21	$28

- AS provision in bidirectional regulation markets is low
- Wind provides more regulation than solar but solar value is often higher
- Hybrid value is often, but not always, higher than standalone value
- Standalone/hybrid value is often, but not always, higher than ISO average regulation price

RD is downward regulation; RU is upward regulation; Total is combined RD and RU

For hybrids, capacity is 10 MW for regulation up/down and 20 MW for total and bidirectional

Sensitivities

- The analysis considers four sensitivities:
  - Max POI – increase POI capacity from 20 MW to 30 MW for hybrids
  - Reg + spin – resources can provide spinning reserve in addition to energy and regulation
  - Spin – resources can only provide energy and spinning reserve
  - High VRE – compare results in high versus low VRE scenarios, using 2030 price forecasts
- Max POI, reg + spin, and spin sensitivities all use 2018 energy and AS prices
- High VRE sensitivity uses 2030 LCG price forecasts from *Impacts of High Variable Renewable Energy Futures on Wholesale Electricity Prices, and on Electric-Sector Decision Making* study
  - Low VRE versus high VRE scenarios (balanced wind/solar, consistent capacity balancing)

Sensitivities: Spinning reserves and POI limits

Incremental value to VRE owner (Δ $/MWh$_{PC}$), 2018 prices

	CAISO	ERCOT	SPP	MISO	PJM	NYISO	ISO-NE
Standalone solar							
Base case	$4.6	$2.3	$0.6	$0.0	$0.6	$0.1	$0.4
Energy + reg + spin	$4.9	$3.0	$0.6	$0.0	$0.6	$0.1	$0.4
Energy + spin	$0.3	$0.8	$0.0	$0.0	$0.0	$0.0	$0.0
Standalone wind							
Base case	$4.7	$1.2	$1.7	$0.1	$1.2	$0.3	$0.7
Energy + reg + spin	$5.2	$1.5	$1.7	$0.1	$1.2	$0.3	$0.7
Energy + spin	$0.5	$0.3	$0.0	$0.0	$0.0	$0.0	$0.0
Hybrid solar							
Base case	$36.7	$16.1	$10.2	$1.7	$23.6	$9.4	$37.1
Max POI	$37.9	$18.2	$11.5	$2.3	$26.7	$10.1	$40.7
Energy + reg + spin	$36.7	$17.8	$10.5	$2.1	$23.5	$9.4	$37.0
Energy + spin	$2.8	$8.3	$0.9	$0.8	$0.8	$0.8	$0.7
Hybrid wind							
Base case	$25.4	$10.1	$5.3	$1.1	$15.3	$4.0	$14.4
Max POI	$27.3	$11.0	$6.3	$1.4	$17.8	$5.1	$20.0
Energy + reg + spin	$25.4	$10.9	$5.4	$1.3	$15.2	$3.9	$14.4
Energy + spin	$1.9	$5.2	$0.4	$0.5	$0.4	$0.2	$0.3

- POI limits have limited impact on hybrid results
- Spinning reserves provide limited incremental value for standalone VRE
  - Result of price cascading and low spin prices
- Spinning reserves provide higher incremental value for hybrids but comparable to base case (energy + reg) only in ERCOT and MISO

Sensitivities: Higher VRE penetrations (2030)

Incremental value to VRE owner (Δ $/MWh$_{PC}$), 2030 price forecast

	CAISO	ERCOT	SPP	NYISO
Standalone solar				
High VRE	$1.4	$6.6	$14.8	$2.0
Low VRE	$0.0	$0.1	$0.0	$0.0
Standalone wind				
High VRE	$1.3	$2.7	$6.6	$1.4
Low VRE	$0.0	$0.5	$0.3	$0.0
Hybrid solar				
High VRE	$34.3	$40.8	$64.1	$20.6
Low VRE	$5.4	$25.2	$7.1	$0.9
Hybrid wind				
High VRE	$21.6	$22.3	$35.9	$10.0
Low VRE	$3.2	$12.0	$3.4	$0.6

Low VRE – "Low VRE" scenario, wind and solar shares frozen at 2016 levels

High VRE – "Balanced VRE" scenario (20% wind, 20% solar)

- High penetrations of VRE may significantly increase value of VRE AS provision
  - Increase in regulation prices, changes in energy-regulation price relationship due to more frequently binding system constraints
- LCG price forecasts do not incorporate higher penetrations of storage, would reduce incremental values for standalone and hybrids

Key issues

Results are sensitive to:

- **AS market participation barriers** – *will standalone VRE be able to participate in AS markets, and what other barriers might exist to AS market participation?*
  - Standalone real-time provision would require dynamic operating limits that account for forecast error
  - Bidirectional regulation may limit VRE participation and optimal storage dispatch
  - May be other economic reasons (e.g., lost renewable energy credit or production tax credit value) that would cause actual value to be diverge from estimates in this study
- **Future AS market volumes and pricing** – *how would higher VRE penetration and VRE and storage participation in AS markets affect the results?*
  - AS markets are thin – ISOs/RTOs have recently procured an average of around 60-800 MW (0.3-0.9% of peak demand) of regulation reserves and 600-2,600 MW (1-4% of peak demand) of spinning reserves (Denholm et al., 2019)
  - ISOs/RTOs may procure more reserves at higher VRE penetration, to address increases in total (MW) net load forecast error, but size of these markets still likely limited
  - AS price structure (energy-reserve price relationship) and price levels may change with higher VRE penetration, incrementally increasing the value of VRE AS provision, but significant increases in storage capacity would likely put downward pressure on prices

Key issues

- **Other or new sources of value** – *what other revenue sources might AS market participation provide, and will new AS products provide additional opportunities for VRE?*
  - **Reduced curtailment**. Previous analysis has shown VRE reserve provision can provide significant benefits by reducing curtailment costs (E3, 2018), which is not captured in this analysis.
  - **Imbalance reserves**. VRE reserve provision can reduce commitment costs. In ISO/RTO markets, many of these benefits would flow to consumers rather than VRE owners, but ISOs/RTOs may also hold additional compensated reserves to address intraday net load forecast error (e.g., imbalance reserves in CAISO).
  - **Flexible ramping reserves**. CAISO and MISO have ramping products that address forecast error between hour-ahead (or 15-minute-ahead) schedules and real-time dispatch.
  - **Primary frequency reserves**. ISOs/RTOs may introduce new products to compensate for the opportunity costs of primary frequency response provision, though current trend is to require these services in interconnection standards.
  - **System inertia**. ISOs/RTOs may create products that pay for provision of system inertia.
  - **Local voltage support**. ISOs/RTOs may create products or contract with resource owners to provide voltage support on the generation side of long-distance transmission lines, to allow more real power flow on transmission lines.

Conclusions

- VRE AS market participation values vary by resource type (standalone/hybrid, solar/wind), perspective (resource owner, system operator), and across ISO/RTO markets
  - Average incremental value to standalone VRE owners can be non-trivial in some markets, but likely not high enough to offset declining energy and capacity value
  - Average incremental value to hybrid VRE owners is relatively high in most markets, but would likely decline with higher penetrations of energy storage
  - Value to system operators is high in most markets, illustrates value of expanding AS market eligibility to enable lower-cost reserve solutions
- Results provide insights around expanding eligibility and changing market rules to enable VRE participation in AS markets
  - Separate upward/downward regulation products could create more value for resource owners and system operators
  - Total AS value of storage (hybrids) will often be higher than standalone VRE but they will relieve different kinds of system constraints, ultimately will likely be advantageous to enable AS market participation by both

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Acknowledgements

This work was funded by the U.S. Department of Energy Office of Energy Efficiency and Renewable Energy, under Contract No. DE-AC02-05CH11231. We would like to especially thank Patrick Gilman, Ammar Qusaibaty, and Paul Spitsen for their support of this work.

The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof, or The Regents of the University of California.

References

- Denholm, Paul, Yinong Sun, and Trieu Mai. 2019. An Introduction to Grid Services: Concepts, Technical Requirements, and Provision from Wind. Boulder, CO: NREL. NREL/TP-6A20-72578.
- Kirby, Brendan and Michael Milligan. 2009. Capacity Requirements to Support Inter-Balancing Area Wind Delivery. Boulder, CO: NREL. NREL/TP-550-46274.
- Ela, Erik, Vahan Gevorgian, Paul Fleming, Yingchen Zhang, Mohit Singh, Ed Muljadi, Andrew Scholbrook, Jake Aho, Andrew Buckspan, Lucy Pao, Vikas Singhvi, Aidan Tuohy, Pouyan Pourbeik, Daniel Brooks, and Navin Bhatt. Active Power Controls from Wind Power: Bridging the Gaps. NREL/TP-5D00-60574.
- Ela, Erik, Robin Hytowitz, and Udi Helman. 2019. Ancillary Services in the United States: Technical Requirements, Market Designs and Price Trends. EPRI, Palo Alto, CA. 3002015670.
- Loutan, Clyde, Peter Klauer, Sirajul Chowdhury, Stephen Hall, Mahesh Morjaria, Vladimir Chadliev, Nick Milam, Christopher Milan, Vahan Gevorgian. 2017. Demonstration of Essential Reliability Services by a 300-MW Solar Photovoltaic Power Plant. Boulder, CO: NREL. NREL/TP-5D00-67799.
- Milligan, Michael, Bethany Frew, Brendan Kirby, Matt Schuerger, Kara Clark, Debbie Lew, Paul Denholm, Bob Zavadil, Mark O'Malley, and Bruce Tsuchida. 2015. Alternatives No More: Wind and Solar Power Are Mainstays of a Clean, Reliable, Affordable Grid. IEEE Power and Energy Magazine 13: 78-87.
- Ellison, James F., Leigh S. Tesfatsion, Verne W. Loose, Raymond H. Byrne. 2012. A Survey of Operating Reserve Markets in U.S. ISO/RTO-managed Electric Energy Regions. SAND2012-1000.
- Rebello, Eldrich, David Watson, and Marianne Rodgers. 2020. "Ancillary services from wind turbines: automatic generation control (AGC) from a single Type 4 turbine." Wind Energy Science 5: 225-236.
- Zhou, Zhi, Todd Levin, and Guenter Conzelmann. 2016. Survey of U.S. Ancillary Services Markets. ANL/ESD-16/1.