The curtailment paradox in a high solar future

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Rising penetrations of variable renewable energy (VRE) in power systems are expected to increase curtailment—the reduction of renewable energy delivered due to oversupply or lack of system flexibility. But while curtailment may be the new normal in the evolving grid, and can even be managed in a way that makes the grid more flexible, it is important to find an optimal level of it to capture the most value out of VRE resources.

While a lack of system flexibility is generally acknowledged to increase curtailment, how individual flexibility options impact curtailment has not been well understood, particularly in high VRE futures. National Renewable Energy Laboratory (NREL) analysts completed the first extensive exploration of how different system flexibility approaches could impact curtailment with higher VRE penetration levels (predominantly solar). Flexibility options include battery storage, thermal generator flexibility, transmission, and allowing VRE and storage to provide operating reserves, among others.

Results—published in a *Joule* article—reveal two key findings that collectively comprise a "curtailment paradox" that emerges as the system evolves to higher solar penetration levels. First, thermal generator flexibility has the biggest impact on VRE curtailment in mid-ranges of solar photovoltaic (PV) penetration, but not at low or high ranges. Second, when VRE and storage are allowed to provide operating reserves, system-wide operating costs and curtailment levels decrease, which, in turn, reduces the economic incentive for PV to provide these reserves with curtailed energy in a wholesale market environment.

Modeling Approach

NREL's analysis used a system that is roughly based on the Los Angeles Department of Water and Power (LADWP) generation and transmission system, leveraging data sets developed for the recently released Los Angeles 100% Renewable Energy Study (LA100). NREL used capacity expansion modeling to establish least-cost future power system build-out scenarios with increasing penetration levels of VRE resources. Next, analysts employed a utility-grade production cost modeling database to optimize least-cost generation and transmission resources to assess the detailed operation of each future build-out scenario.

This is the first time this full suite of models has been used for a realistic, highly resolved system in high PV futures to identify which operational factors contribute most to curtailment and the potential value of PV to provide operating reserves with curtailed energy.

Paradox 1: Thermal Generator Flexibility Has the Biggest Impact on Curtailment Only at Mid-PV Penetration Levels

Thermal plant flexibility—ramp rate, minimum generation levels, and minimum up-and-down time—allows the power system to respond as needed to grid fluctuations and maintain supply-demand balance.

In the study, NREL made the counterintuitive observation that thermal plant flexibility has a much larger impact on VRE curtailment in a "transition zone" at mid-PV levels (roughly 25%–40% in the study system) than at lower or higher levels. Of the various aspects of thermal generator flexibility, minimum generation levels have the biggest impact on curtailment in this zone.

However, when PV penetrations are low (about 20%), there is not enough VRE for changes in thermal flexibility to have a meaningful impact on the system. When PV penetrations are higher (about 45%), there is not enough incentive to use the remaining thermal capacity to adjust operations and yield significant curtailment impacts.

"We also call the transition zone the "Goldilocks zone' where it is just the right combination of PV and thermal generators to result in thermal flexibility impacts to curtailment," said Bethany Frew, NREL senior energy analyst and principal investigator of the study.

This aspect of the curtailment paradox reveals the importance of the evolution and interaction of solar with the rest of the system, especially when it comes to thermal plant flexibility in power systems that are transitioning from thermal-dominant to VRE-dominant fleets. It also suggests that a phased approach may be needed to support the ongoing power system transformation.

Paradox 2: Using VRE and Storage for Operating Reserves Means Lower Operating Costs and Curtailment, But Reduced Revenue

Curtailed and stored renewable energy has increasingly been seen as a potential source for operating reserves, or the capacity available to the system operator within a short interval of time to meet demand during events like load forecasting errors or scheduled outages.

As modeled in the study, simulated high-PV-penetration scenarios in which VRE and storage resources are not allowed to provide operating reserves yield significant increases in curtailment and operating costs—pointing to the overall value of allowing these resources to provide operating reserves.

However, this value does not necessarily translate to increased revenue potential in a wholesale market environment—which represents the second aspect of the curtailment paradox.

"Allowing VRE and storage to provide operating reserves results in low prices, which reduces incentives for PV to provide operating reserves with curtailed energy," Frew said. "This aspect of the solar curtailment paradox reveals the importance of proper alignment of grid system value and compensation."

Storage built for capacity and energy-shifting services often has spare capacity for reserves, especially during times of overgeneration. Because storage has near-zero cost, it results in lower overall operating reserve prices, especially during PV curtailment. Allowing storage to provide operating reserves also reduces the amount and hours of curtailment, which limits the times when PV could use curtailed energy to provide operating reserves.

Add VRE on top of storage, and prices decrease even more. Overall, there is little incentive for PV to provide operating reserves with curtailed energy. It cannot compensate for reduced revenues from greater levels of curtailment and declining energy prices with high levels of VRE.

"We found PV provides system value without sufficient opportunity for monetary compensation," Frew said. "Market designers may need to revise operating reserve eligibility rules and compensation structures as PV penetrations increase."

Future Work

Overall, the study highlights the very nuanced nature of flexibility and its role in the solar curtailment paradox, and indicates that storage and thermal generators are significant drivers of a system's flexibility needs (and curtailment levels) with high solar penetration levels.

Future work could explore other sensitivity factors with additional storage penetration levels and various system configurations. In addition, a full cost-benefit analysis of thermal generator flexibility upgrades could assess the overall cost competitiveness with storage and other flexibility options as power systems evolve to greater VRE penetration.

More information: Bethany Frew et al. The curtailment paradox in the transition to high solar power systems, *Joule* (2021). DOI: 10.1016/j.joule.2021.03.021

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