Curtailment 101: Understanding the Basic Economic Trade-offs

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Abstract

This article summarizes the basic economic trade-offs of renewable energy curtailment. We begin by defining curtailment and when/why grid operators use it, drawing on examples from different regional electricity markets. We provide a simple economic framework for balancing marginal benefits and costs and distinguish between the short- and long-run costs of curtailment.

1. Introduction: Defining Curtailment

Increasing penetration of variable renewable energy (VRE) such as wind and solar has impacted wholesale electricity markets in a variety of ways, including (but not limited to) impacts on the variability of wholesale prices (Johnson & Oliver, 2016; 2019), system balancing (Hirth & Ziegenhagen, 2015; Godwin & Oliver, 2024), and the costs associated with responding to forecast uncertainty (Weber & Woerman, 2024).

An additional and important effect is that in markets with a high penetration of VRE resources, grid managers increasingly resort to *curtailment* of wind and solar generation as a means of maintaining system balance and avoiding negative prices (Bird et al, 2014; Henriot, 2015; Davis et al, 2023). As defined by Bird et al. (2014), curtailment refers to "a reduction in the output of a generator from what it could otherwise produce given available resources, typically on an involuntary basis." Henriot (2015) further distinguishes between "economic curtailment" and "technical curtailment," where the former is conducted based on marginal costs and benefits and the latter is done to ensure safety of operations.[1]

Curtailment of VRE generation, both in absolute terms and as a percentage of VRE generation, has grown significantly in recent years across many markets. Figure 1 depicts curtailment as a share of total solar or wind generation in select US markets with high penetration of VRE generation. Similar trends have been observed in recent years in several European markets, Australia, and elsewhere.

At low to medium levels of VRE penetration, localized congestion on the transmission network is the main factor in determining the appropriate level of VRE curtailment, whereas at high penetration levels, curtailment will depend more on whether VRE generation exceeds total customer load at a given point in time (Burke and O'Malley, 2011). To distinguish between these two different mechanisms, for the remainder of this article we refer to them as *congestion-based* curtailment and *load-based* curtailment, respectively. Below, we discuss the basic economics of these two curtailment approaches, exploring the various costs and benefits of each and distinguishing between short-run and long-run considerations. We conclude with some thoughts on opportunities for continuing research on VRE curtailment.

2. Congestion-based versus Load-based Curtailment

We define *congestion-based curtailment* as the scenario wherein, holding the level of electricity demand fixed, localized congestion on the transmission grid is the main driving factor behind curtailing VRE resources. In CAISO, for example, a quick look at daily curtailment reports for June 2024[2] shows that the vast majority of solar curtailment was in the category labelled "Local Economic," defined as curtailment based on "market dispatch of generators with economic bids to mitigate local congestion," which "occurs when available least-cost energy cannot be delivered to some loads because transmission facilities do not have sufficient capacity to deliver the energy."

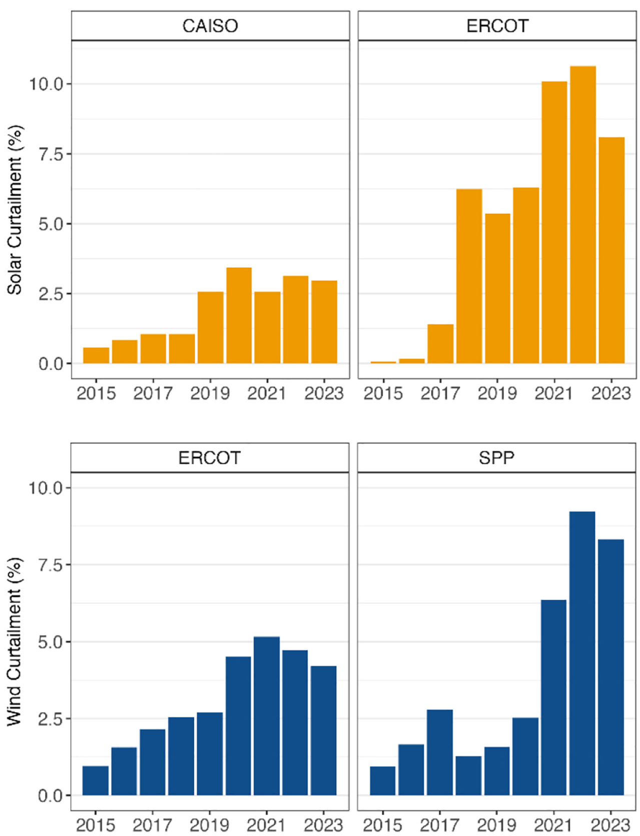

Figure 1: Curtailment as a share of total solar or wind generation in select US markets
Notes: This figure shows curtailment as a share of total solar or wind generation in three large regional power markets in the US. CAISO refers to the California Independent System Operator. ERCOT is the Electricity Reliability Council of Texas. SPP is the Southwest Power Pool. Source: Lawrence Berkeley National Lab, Utility Scale Solar Report 2024 *and* Land-Based Wind Market Report 2024

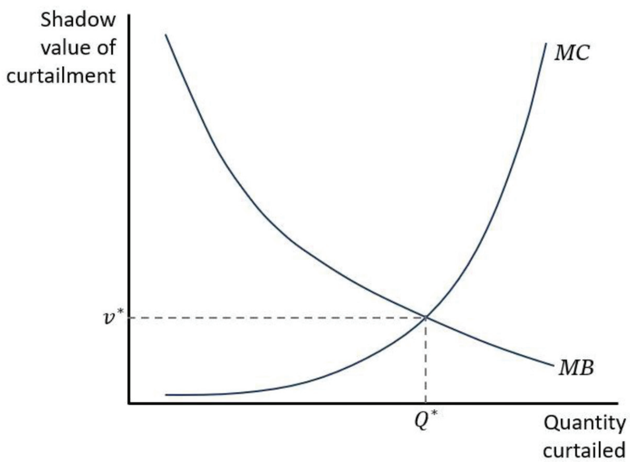

Figure 2: Balancing the marginal benefits and marginal costs of congestion-based curtailment

In such situations, to serve load the grid operator must dispatch higher-cost units at other locations on the transmission network so as to circumvent locally congested transmission lines. This inherently leads to allocative inefficiencies and higher locational marginal prices, and potentially to increased emissions, depending on the profile of generators being dispatched to serve load.

As with any economic activity, the optimal level of congestion-based curtailment of VRE generation can be boiled down to balancing marginal benefits with marginal costs, depicted graphically in Figure 2.[3] Curve *MB* plots the marginal benefits of curtailment, which include reduced system costs, balancing services, and grid reliability. Curve *MC* plots marginal costs, which include increased emissions/pollution (i.e., external costs) per MWh of total generation and allocative inefficiencies related to deviations from the merit order. We discuss these marginal benefits and costs in greater detail below and note here that they may, at least in part, prove difficult to measure empirically. Yet in theory, optimizing congestion-based curtailment is straightforward. The intersection of the two curves—that is, where *MB*=*MC*—yields the optimal quantity of renewable generation to be curtailed, denoted Q^*. At this optimal quantity, the shadow value per MWh curtailed is v^*, which represents the optimal compensatory payment that should be made to renewable generators required to forgo sales in order to comply with the system operator's curtailment needs.

The alternative scenario of *load-based curtailment* occurs when the transmission network is typically uncongested (or transmission constraints are non-binding) and curtailment is needed to match the supply of power to the actual demand. Again, referring to CAISO's curtailment reports, the second largest category of curtailment, "Economic - System," is based on "market dispatch of generators with economic bids to mitigate system-wide oversupply."

Load-based curtailment is intuitively somewhat simpler in that there is no need to supply power that customers do not want to consume. However, other factors, such as the so-called *minimum load problem*, complicate load-based curtailment decisions. As explained by Simshauser and Wild (2025), the minimum load problem occurs when high VRE generation conflicts with an oversupply of conventional generation units with "must run" requirements. These constraints may become binding, for example, during daytime hours in markets with high penetration of solar photovoltaics, as net load on the system drops[4] below the total generation requirements of must-run plants. Similarly, high wind generation at night, when daily load is at its minimum, may also encounter such constraints. The key point is that, curtailment of VRE generation is often imposed in such situations, both as a means of avoiding negative prices and to maintain system balance given the inability to cycle off must-run generation.

Note that a key challenge here is the high cost of electricity storage relative to the costs of curtailment. However, as the levelized cost of storage is expected to decline with continuing innovation, rapid deployment of utility-scale energy storage technologies will allow power from VRE resources that would otherwise be curtailed to instead be stored for prolonged duration at low cost for later use during periods of low VRE and high demand.

3. Short-run versus Long-run Considerations

Curtailment of renewable generation is associated with several external costs (e.g., emissions) and allocative inefficiencies that are typically realized in the short-run, which in turn can have long-run implications for price signals and the speed of the energy transition.

In the short-run, with the demand for electricity fixed, curtailing VRE generation often results in greater generation from fossil fuel sources to meet net demand. The emissions costs of curtailment therefore depend on the renewable technology being curtailed, the emissions profile of the conventional generation that replaces it in the merit order, and the season. For instance, Doshi (2024a) shows that wind curtailment in ERCOT due to grid congestion led to approximately $150 million worth of excess emissions (both CO_2 and local pollutants) in 2020. Another implication of both congestion-based curtailment and load-based curtailment resulting from the minimum load problem described above is the allocative inefficiency which stems from dispatching out-of-merit order sources of electricity. This in turn can lead to market power concerns with annual welfare losses on the order of hundreds of millions of dollars, as such costs are ultimately passed through to electricity consumers (Woerman 2019, Doshi 2024b).

In the long-run, persistence of renewable curtailment implies forgone revenue to renewable energy developers. This in turn can dampen investment in renewable generation in the market as curtailment signals lower returns to investment in that region. A natural consequence of this lower renewable investment is the continued reliance on conventional thermal (i.e., fossil fuel) power generation. From a policy maker's perspective, this could be concerning if the goal is faster decarbonization.

Increasing curtailments also signal the need for transmission policy reform (Doshi 2024a). This means investing in high-capacity transmission lines to relieve grid congestion or transmission upgrades which may avoid certain permitting requirements associated with building new transmission lines (Davis et al. 2023).[5] Investments in utility-scale battery storage will also be useful as it allows grid managers to store unused power from renewable sources rather than resort to curtailment. Electricity storage may also help alleviate inefficiencies from localized congestion on the transmission grid.[6] This effectively reduces the amount of renewable power curtailed while also reducing the emissions from fossil fuel sources.

4. Concluding Remarks

Curtailment of renewable resources is of interest and concern to policy makers, renewable developers, grid operators, and academics alike. Yet several gaps exist in the current economic and policy literature. We highlight two key areas of continuing research related to curtailment that will be important for electricity markets going forward.

First, research into the economics of energy storage is imperative for understanding its effectiveness in reducing load-based curtailment and in preventing allocative inefficiencies resulting from congestion-based curtailment in the short run. Second, while the current literature mainly looks at short-run costs associated with VRE curtailment (e.g. Doshi, 2024a), research into how curtailment affects long-run outcomes like renewable investment will be beneficial. For example, the combination of increasing congestion-based curtailments and the projected rise in load across markets due to the construction of energy-intensive data centers could result in increasing emissions from fossil fuel sources. Such issues are likely to be an important consideration for policy makers over the coming decades, in terms of how to effectively balance investments in new load, utility-scale storage facilities, transmission infrastructure, and VRE generation. Careful quantification of the long-run costs of increasing curtailments will provide key insights into strategies that policy makers and market operators may undertake to address them.

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Footnotes

[1] For brevity, we use the term `curtailment' throughout to refer specifically to economic curtailment.

[2] https://www.caiso.com/library/wind-solar-real-time-dispatch-curtailment-reports-jun-2024

[3] A more rigorous theoretical treatment is available in Henriot (2015).

[4] Now famously known as the "duck curve" phenomenon.

[5] Transmission expansion has several other market benefits besides lower congestion. For instance, in Texas, transmission expansion lowered the costs of hedging risk for market participants in ERCOT (Doshi and Du, 2021).

[6] Similar effects of storage in relation to transmission congestion have been observed on the natural gas pipeline network (Oliver et al, 2014).

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