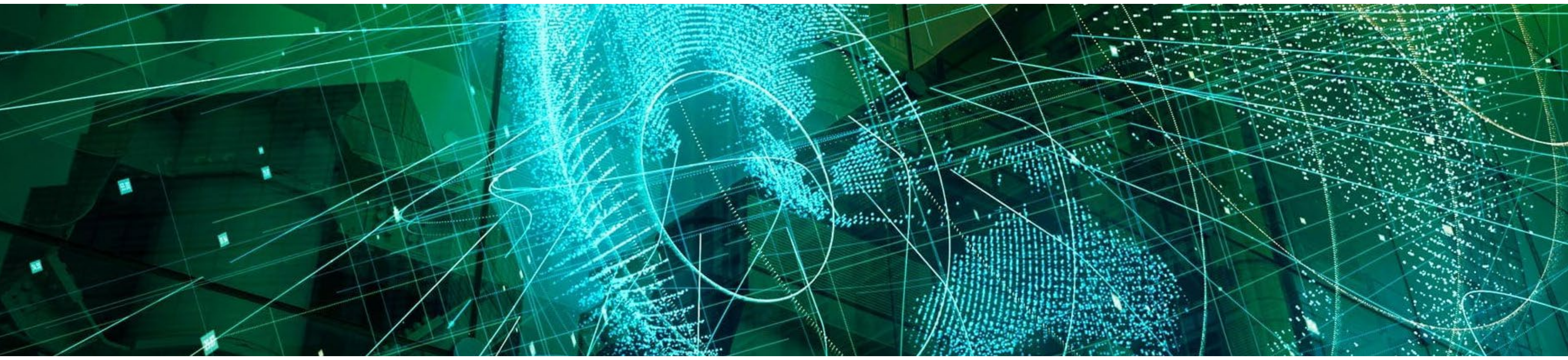
GLOBAL PST CONSORTIUM

Global Power System Transformation Consortium

Rapidly accelerating transitions to advanced low emission power systems in collaboration with power system operators in all regions



What Is Power System Curtailment?

Most practitioners are familiar with the curtailment of variable renewable energy (VRE) resources like wind and solar photovoltaics as a reduced production of power relative to what would be available from the wind and solar resource. This curtailed energy is the difference between the total available energy and actual production. More generally, curtailment is the intentional reduction of instantaneous power from supply or demand resources to aid balancing of the electricity grid. It is more often applied to supply-side resources whose output is reduced relative to what would be available from the primary resource, regardless of technology type. This general definition is like the well-known "dispatch down" instruction a system operator would use for any resource to reduce their generation.

When the supply of wind and solar photovoltaics exceeds the demand for electricity, considering the operational constraints of remaining generators, operators cannot further integrate the available wind and solar energy and instead curtail (in the absence of demand-side participation, expanded networks, storage technologies or exports to neighboring systems). While curtailment can be a cost-effective alternative to network expansions when installing VRE, too much curtailment reduces the economic benefits of potential new wind and solar, considering their low marginal costs. Curtailment also limits the extent to which electric grids can decarbonize using VRE alone by limiting the contributions of VRE capacity. Building storage, implementing demand-side management, and/or expanding the network can help reduce curtailment and increase the use of available energy from VRE generators.

In summary, VRE generators may have their output curtailed for two main reasons: (1) oversupply and system security, and (2) transmission congestion and local constraints. **Figure 1** shows examples of both types from two system operators (EirGrid in Ireland and the California Independent System Operator [CAISO] in California, USA). These categories are described further in the next section.

What are the two main classes of curtailment?

System-Wide Oversupply and System Security

To balance the supply and demand of electricity system-wide, VRE generators across the system may have their output curtailed in times of oversupply. Systems with significant solar capacity may experience oversupply in the middle of the day, for example. Systems with significant wind capacity may experience excess wind generation overnight in shoulder months when electricity demand remains low. Wholesale energy markets can also facilitate supply-demand balancing through economic curtailment where VRE generators reduce production as a result of reduced wholesale market prices (in many instances, wholesale prices can also become negative throughout the year). In cases of out-of-market interventions (e.g., production tax credits), times of oversupply with negative wholesale market prices may still result in VRE generators choosing to produce due to the relative trade-off between negative wholesale market prices and out-of-market revenues.

Operators also curtail VRE to stay within established system-wide stability thresholds and to maintain system frequency performance. For example, operators may require grids to always maintain a certain number of synchronous generation units online (committed) (e.g., based on established minimum inertia levels, limiting contributions from non-synchronous VRE generators). However, these structurally inflexible approaches to unit-commitment (amongst others, including underlying engineering and market design deficiencies) will likely require adaptation as more VRE is added.

Operating reserve requirements can also result in wind and solar curtailment to maintain headroom for flexible reserve providers to increase their output as needed (including wind and solar), balancing supply and demand.

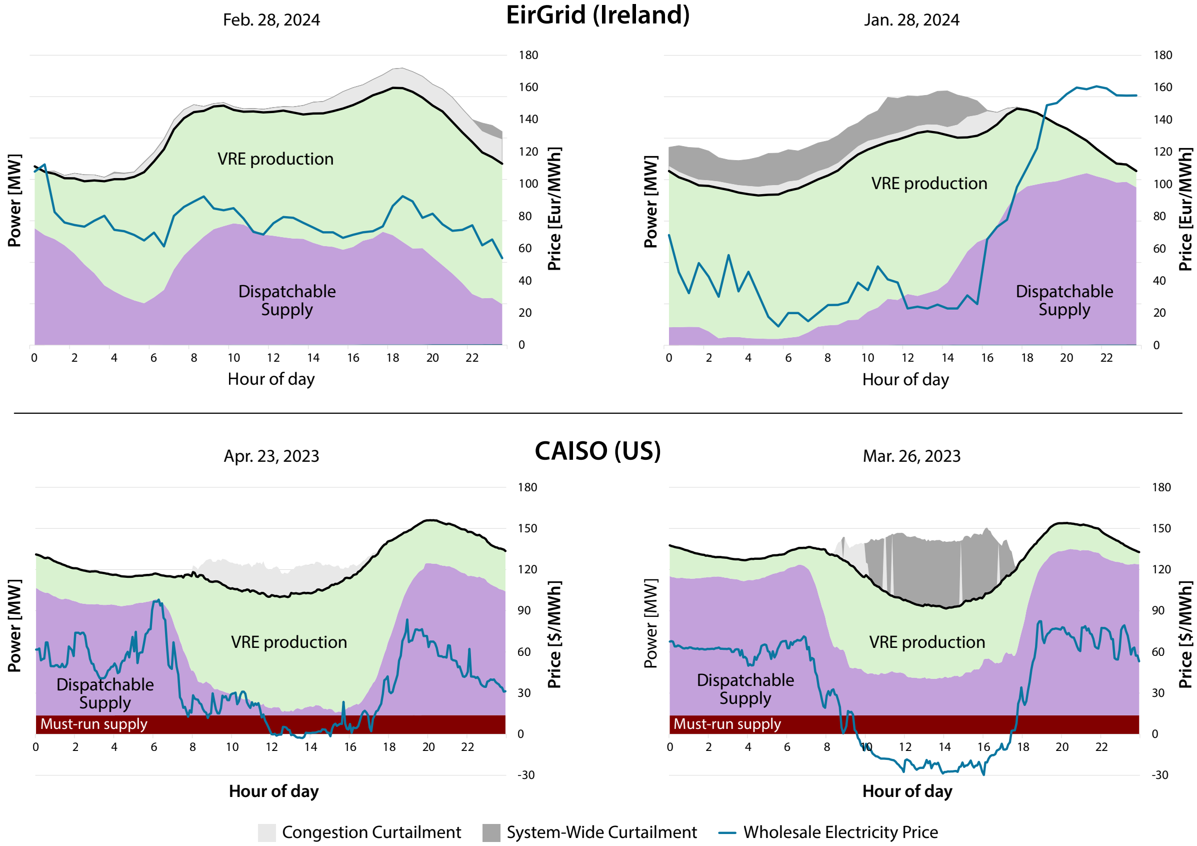


Figure 1. Congestion vs. system-wide curtailment dispatch stacks for one example day (EirGrid and CAISO)
(Image created by authors, based on data from EirGrid and CAISO)

Congestion and Local Constraints

Distinct from system-wide considerations, local network limitations may restrict generation at some VRE plants. Operators may curtail a specific VRE plant or set of plants to prevent overloading transmission lines moving power across interfaces. Expanding transmission capacity in regions prone to high levels of congestion can help reduce curtailment and maximize the use of available VRE resources.

To maintain local voltage stability, system transient stability, and related performance of protection systems, operators may curtail VRE generators to keep synchronous generation units online (operating at minimum generation levels) to protect against known negative impacts of disturbances. To achieve similar services, alternative mitigation measures such as network strengthening—as well as deploying synchronous condensers and grid-forming inverter-based resources—could also be implemented.

Finally, local network outages due to planned maintenance, system upgrades, or faults may result in curtailment of VRE resources if outages reduce the ability to export power to the rest of the grid.

How Prevalent Is Curtailment?

Annual contributions from wind and solar have increased across many power systems around the world (**Figure 2** shows this trend for the past 5 years for a group of system operators). However, it is difficult to extract specific insights with respect to "typical" curtailment levels for different levels of VRE share. Each system has a unique portfolio contributing to its initial and final VRE share as well as underlying system-specific attributes (supply-side flexibility, network strength, resource location relative to demand centers, and interconnectivity with other system operators) that influence curtailment levels.

How Do System Operators Manage Curtailment?

Six Global Power System Transformation Consortium system operators were surveyed about curtailment: the Australian Energy Market Operator (AEMO), CAISO, Ireland's EirGrid, Denmark's Energinet, the Electric Reliability Council of Texas (ERCOT), and Great Britain's National Energy System Operator (NESO). The following sections detail these system operators' procedures for managing curtailment as communicated in survey responses and publicly available documentation.

Each system operator reports using VRE curtailment as a tool in regular operations as well as in emergency situations. VRE curtailment is just a special case of dispatch in which all resources have the potential to be curtailed based on unit-commitment and economic dispatch principles. In regular operations, curtailment is implemented system-wide to reduce oversupply (and manage system security) or locally to manage congestion and other network constraints. In emergency situations, VRE resources may be curtailed (or shut down) as needed for system operators to resolve acute network issues and maintain stability following a major disturbance. Curtailment definitions, compensation mechanisms, and implementation vary across system operators. This section highlights key practices from the system operators interviewed.

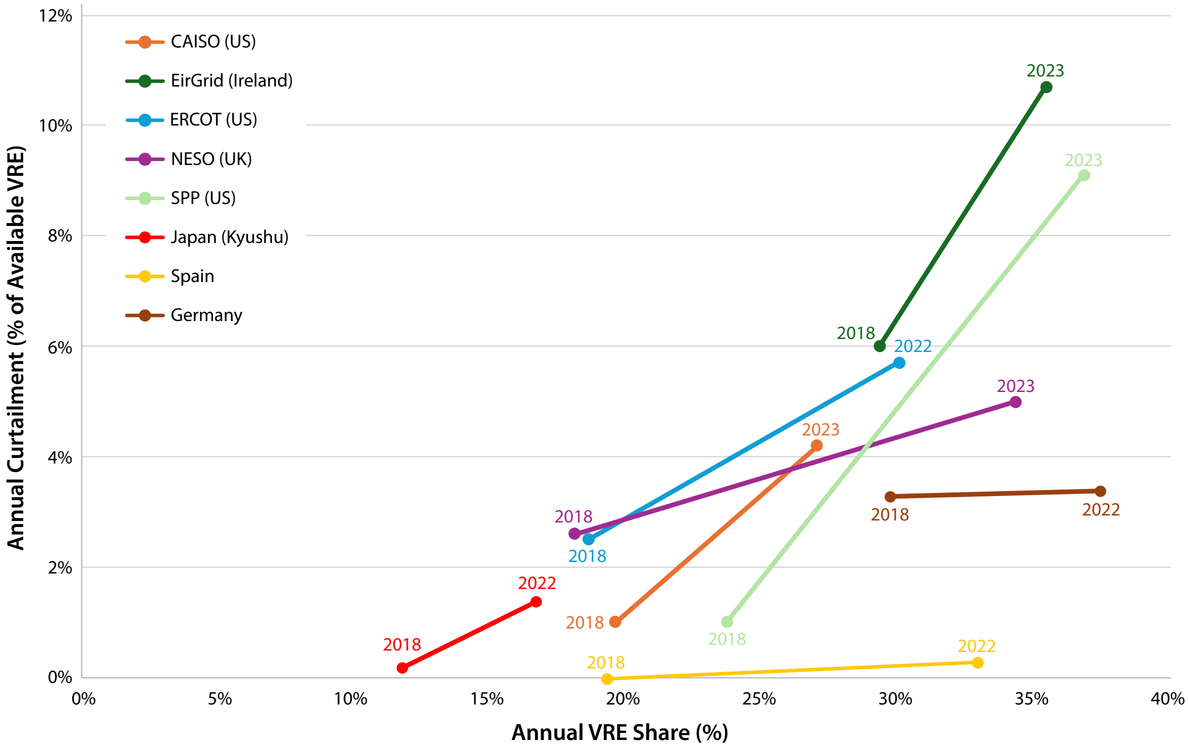


Figure 2. VRE curtailment vs. annual VRE contribution for selected system operators
(Image by authors; SPP - Southwest Power Pool, NESO – National Energy System Operator)

Curtailment in Transmission vs. Distribution Networks

CAISO, ERCOT, and AEMO manage curtailment in their transmission networks. In Ireland, Great Britain, and Denmark, the system operators (EirGrid, NESO, and Energinet, respectively) similarly apply curtailment in transmission networks for transmission constraints and system-wide curtailment. In addition, the distribution system operators in these countries (e.g., ESB in Ireland or Western Power Distribution, among others, in Great Britain) monitor distribution constraints and manage curtailment in their distribution networks accordingly.

Enabling Generator Curtailment

Connection agreements between transmission owners in Great Britain (e.g. National Grid Electricity Transmission, amongst others), and generators include curtailment provisions. For example, generators can enter "non-firm" connection agreements in which they assume liability for curtailment if they choose to proceed with connection before the network is able to support the additional generation (commonly referred to as a "connect-and-manage" philosophy).

Curtailment Compensation

Some system operators compensate VRE generators for different types of curtailment through various mechanisms, and most depend on the underlying electricity market structure. Other generators are not directly compensated for operating below their full capacity and are instead typically compensated using other market or regulatory mechanisms.

NESO compensates for all curtailment, while Energinet compensates for all curtailment unless it is due to a planned transmission outage. In Ireland and Northern Ireland, approaches and policies applied by EirGrid to curtailment compensation have evolved over the years and further changes are being considered due to changes in EU regulations. EirGrid distinguishes between system-wide curtailment and local congestion-induced curtailment, currently compensating only for the latter through revenues received from ex-ante energy markets when these resources are deemed firm (with exceptions for short-term transmission outages). EirGrid defines firm resources as the proportion of a generating plant's rated capacity that can consistently be safely accommodated on the network (established through simulation studies). Dispatch down of resources seen as non-firm for either local congestion or system-wide curtailment reasons are treated as imbalances. However, work has been progressing on developing a potential future modification to market rules such where curtailment for system-wide reasons is compensated similar to local congestion curtailment. EirGrid also applies a minimum threshold of curtailed energy as a percentage of a generator's available energy that must be met to receive compensation. EirGrid does not currently compensate for curtailment in distribution networks. Further, net costs arising due to curtailment settlement are recovered (amongst other costs), through an annual regulator-approved Imperfections Tariff on all suppliers. This is based on simulated market dispatch forecasts comparing models with and without network and system constraints to determine expected volumes, and on the actual costs arising in the past. Any variance between the amount collected under tariff and actual expenditure is recovered or returned by adjusting the following years tariff. This is based on simulated forecasts using constrained modeling to determine expected volumes, whilst actual compensation is determined ex-post based on the Trading and Settlement Code.

As outlined in system-specific electricity market rules and procedures, some system operators allocate curtailment compensation to generators using balancing market settlement mechanisms (like in NESO in Great Britian).

Cost of Curtailment vs. Network Upgrades

In their planning processes, system operators often estimate the cost of curtailment relative to network upgrades to understand when (and where) curtailment may be more cost-effective. AEMO has found cases in which curtailment is more efficient than expanding existing networks or building new storage in particular locations. Alternately, AEMO also recognizes situations in which transmission expansion offers greater benefits by reducing curtailment and thus enabling more widespread resource-sharing. Energinet in Denmark has repeatedly found that, in the long term, excessive curtailment costs more than expanding transmission networks. However, they have simultaneously found that curtailment can be used in the short term and as a strategy to influence the scope of network expansions. This decision is highly system-dependent and location-specific.

Issuing Curtailment Instructions

Initial curtailment assessments are commonly done many hours ahead of real time. NESO conducts a daily assessment of network constraints that is updated 4–8 hours before real time and is used to inform where and how much curtailment will be needed. Closer to real time, NESO begins communicating instructions to generators and using more-detailed security analysis tools, including power-flow assessments, to further update instructions.

System operators, including ERCOT and CAISO in the United States, determine curtailment as part of their security-constrained economic dispatch processes, which update optimal dispatch instructions according to current network constraints, demand, and generator availability. Security-constrained economic dispatch automatically curtails VRE dispatch as needed to satisfy constraints.

Once curtailment is deemed necessary, EirGrid instructs VRE resources (either system-wide or within a constraint group, depending on the reason for curtailment) to curtail by issuing active power control set points for each generator that limit output proportional to capacity. VRE resources that are not compliant with controllability requirements (without remote control and grid-responsive capabilities) are instructed to curtail first, followed by compliant resources, and finally by recently energized VRE units undergoing commissioning.

NESO typically incentivizes curtailment through market mechanisms (as previously mentioned). However, in emergency situations, they will bypass the balancing market and instruct generators directly to reduce output as needed to maintain system security.

Conclusion

Power system curtailment is a well-established mechanism used by system operators to manage surplus supplies of VRE resources. However, the implementation of curtailment varies considerably between system operators, exhibiting various levels of sophistication. A range of curtailment levels exist across system operators depending on their local context with respect to existing operational practices, market arrangements, resource flexibility, and storage deployment and transmission networks (including interconnectivity with neighboring systems). As the integration of VRE into electricity grids around the world continues to expand, trends have emerged to manage and compensate for local congestion and system-wide curtailment, reflecting continually improving practices for curtailment whilst simultaneously also revealing the unique characteristics of individual electricity grids.

Further Reading

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