Digital Grid: Innovative Solutions to Renewable Energy Curtailment in Power Markets

BY GAVIN FLANAGAN

Abstract

Renewable energy curtailment presents significant economic challenges in power markets. This article examines key drivers—cost, geographic constraints, congestion, and supply–demand imbalances—and shows how future grid enhancement, smart grid technology, and distributed energy resources can effectively address energy curtailment challenges through a multifaceted, adaptive approach.

Background

Energy curtailment in power markets has been a persistent challenge globally. As the levelized cost of energy (LCOE) for renewables declines, adoption rates have increased, leading to higher instances of curtailment due to transmission constraints and grid congestion. In the United States, curtailment remains a prominent grid challenge. According to the U.S. Energy Information Administration, "CAISO curtailed 2.4 million megawatthours (MWh) of utility-scale wind and solar output, a 63% increase from the amount of electricity curtailed in 2021" (U.S. Energy Information Administration, 2023), and in ERCOT's grid, the "average annual wind curtailment was around 16%. Monthly averages ranged from about 24–28% of potential wind generation from February–April" (NREL, 2010).

Internationally, curtailment trends have also been notable. In 2011, China experienced significant curtailment: "the curtailed wind power generation in 'three-N region' (North China, Northeast, and Northwest) was up to 12.3 billion kWh, eventually causing a loss of 6.6 billion CNY for wind farm investors, and 16.23% of wind power generation" (Li et al., 2015). Similarly, in Germany and the United Kingdom, "4.4% of German and 5.6% of (metered) British wind energy was curtailed in 2016, a total of 4.65 TWh" (Joos & Staffell, 2018).

However, while the implementation of renewable energy is both environmentally and financially advantageous, it has unfortunately led to increased curtailment costs. Underlying these costs are persistent transmission challenges. Aging and under-capacity infrastructure—compounded by geographic constraints and intermittency issues—necessitate low-cost solutions such as expanding existing capacity, digitizing energy assets to extend their lifespan, leveraging advanced AI technologies, and deploying distributed energy resources to alleviate grid burdens and costs.

Grid Enhancement Technologies

Globally, transmission remains a top priority as electricity demand increases. In countries such as the United States, "70 percent of transmission lines are over 25 years old and approaching the end of their typical 50–80-year lifecycle" (U.S. Department of Energy, 2023). Although building new high-voltage transmission lines would ideally resolve congestion and location-based constraints, intensive capital requirements, long lead times, and supply chain challenges make such expansion difficult. "While global investment in power transmission grew by 10% in 2023 to reach $140 billion, this figure would need to exceed $200 billion annually by the mid-2030s to meet rising electricity demand" (IEA, 2025).

Amidst these high capital costs, emerging technologies such as Dynamic Line Ratings (DLR) have successfully navigated the "Innovation Valley of Death" due to their modular design, commercial viability, and lower fixed and variable costs compared to new transmission lines. By utilizing real-time monitoring of ambient weather conditions and two-way communication methods, DLR improves the capacity of existing transmission lines—alleviating congestion pricing in high-demand areas where energy curtailment is necessary for grid stability.

Some case study examples demonstrate that the implementation of DLR technology has yielded significant improvements in line capacity and cost reduction. For example, "Oncor Electric Delivery, a US utility, implemented DLR and observed ampacity increases of 6–14% for 84–91% of the time" (Lee, Nair, & Sun, 2022) and in Germany, "Ville Ost, which links Rommerskirchen and Sechtem, had 393 hours of redispatch, resulting in a 273 GWh reduction at one end and a 271 GWh increase at the other, totaling 431 GWh redispatched. Applying DLR on this line would result in a 25% capacity increase on the line 50% of the time, and a 15% gain 90% of the time" (International Renewable Energy Agency, 2020).

Smart Grid Technology

The smart grid represents a transformational shift in how electricity is managed and distributed. It encompasses advanced technologies that enable real-time monitoring, automation, and data exchange between utilities and customers. Smart grids, equipped with sensors, smart meters, and robust communication networks, enhance the efficiency and reliability of electricity distribution.

By leveraging these technologies, smart grids facilitate better utilization of transmission and distribution infrastructure, reduce congestion, and improve resilience against outages. For example, "ConEdison increased its 4kV substation capacity by 2.8 percent under peak conditions using CVR, resulting in a net savings of $15.7 million" (U.S. Department of Energy, 2016).

Furthermore, smart grids enable more efficient use of capital assets and reduce operating costs through advanced monitoring and preventative maintenance. For instance, "O&M savings from CVR formed the largest portion by far of Duke Energy's 20-year smart grid business case, with a net-present value of more than $155 million" (U.S. Department of Energy, 2016). These advancements in cost savings and energy optimization demonstrate how smart grids contribute to a more efficient and reliable energy infrastructure.

Distributed Energy Resources

Distributed energy resources (DERs) offer a promising solution for addressing renewable energy curtailment and optimizing power markets. By providing power supply and services close to where they are used, "DERs can lower costs for consumers, improve the reliability and resilience of the power grid" (ACEEE, n.d.). This capability not only stabilizes the grid but also enhances its overall efficiency.

Energy efficiency measures enable customers to reduce their energy consumption while still receiving high-quality services. DERs can also provide capacity during peak periods, reducing the risk of brownouts and blackouts. "DERs can also be used to create microgrids—"islands" with their own generation and storage that can isolate from the larger grid in the event of a system-wide outage" (ACEEE, n.d.). By shaping daily load profiles, DERs help flatten peak demand periods and fill valleys of low demand, thereby optimizing energy production and consumption and reducing strain on the transmission system.

DERs encompass a diverse array of technologies, including distributed solar photovoltaics (PV), distributed wind, distributed energy storage, and hybrid systems, which primarily serve local consumers. The growth of distributed PV is dramatic, with "the number of U.S. residential PV systems increasing from 89,000 in 2010 to 4.7 million in 2023. In 2023 alone, almost 800,000 residential PV systems were installed in the United States" (Wood Mackenzie, 2024). Large-scale adoption of PV technology is evident, as "last decade has shown a sharp, though now steadying, decline in costs, driven largely by photovoltaic (PV) module efficiencies" (NREL, 2021) and "Since 2010, there has been a 64%, 69%, and 82% reduction in the cost of residential, commercial-rooftop, and utility-scale PV systems, respectively" (NREL, 2021). Although the fixed costs of renewable energy sources such as solar and wind remain high, their low variable costs and declining levelized costs will continue to drive growth. In addition, with the "deployed capacity of energy storage expected to quadruple globally by 2030 compared to 2018" (DOE, 2020), the prevalence of distributed energy resource technologies is likely to grow in tandem.

Summary

Renewable energy curtailment is a complex challenge that intertwines issues of cost, congestion, technological limitations, and geographic constraints. As renewable penetration continues to rise, no single solution will suffice. Instead, a coordinated strategy—one that integrates grid digitization, smart grid technologies, and distributed energy resources—is essential to optimize grid performance and support the ongoing global energy transition. Tailored solutions, adapted to the specific market, geographic, and resource conditions of each region, will be crucial in mitigating curtailment and ensuring a resilient, sustainable energy future.

References

Aniti, L., & Smith, S. (2023, October 30). *Solar and wind power curtailments are rising in California - U.S. energy information administration (EIA)*. Solar and wind power curtailments are rising in California - U.S. Energy Information Administration (EIA). https://www.eia.gov/todayinenergy/detail.php?id=60822#

NREL. Examples of wind energy curtailment practices. National Renewable Energy Laboratory; July 2010. Available at: ⟨http://www.nrel.gov/docs/fy10osti/48737.pdf⟩.

Li, C., Shi, H., Cao, Y., Wang, J., Kuang, Y., Tan, Y., & Wei, J. (2015). Comprehensive review of renewable energy curtailment and avoidance: A specific example in China. *Renewable & Sustainable Energy Reviews*, *41*, 1067–1079. https://doi.org/10.1016/j.rser.2014.09.009

Joos, M., & Staffell, I. (2018). Short-term integration costs of variable renewable energy: Wind curtailment and balancing in Britain and Germany. *Renewable & Sustainable Energy Reviews*, *86*, 45–65. https://doi.org/10.1016/j.rser.2018.01.009

United States Department of Energy. (2023, October 19). What does it take to modernize the U.S. electric grid? https://www.energy.gov/gdo/articles/what-does-it-take-modernize-us-electric-grid

Rising component prices and supply chain pressures are hindering the development of transmission grid infrastructure - news. International Energy Agency. (2025, February 25). https://www.iea.org/news/rising-component-prices-and-supply-chain-pressures-are-hindering-the-development-of-transmission-grid-infrastructure

Lee, T., Nair, V. J., & Sun, A. (2022). *Impacts of Dynamic Line Ratings on the ERCOT Transmission System*. https://doi.org/10.48550/arxiv.2207.11309

International Renewable Energy Agency. (2020). Innovation landscape brief: Dynamic line rating. International Renewable Energy Agency. Retrieved March 6, 2025, from https://www.irena.org//media/Files/IRENA/Agency/Publication/2020/Jul/IRENA_Dynamic_line_rating_2020.pdf

Distribution Automation: Results from the Smart Grid Investment Grant Program. www.energy.gov. (2016, September). https://www.energy.gov/sites/prod/files/2016/11/f34/Distribution%20Automation%20Summary%20Report_09-29-16.pdf

Distributed Energy Resources. ACEEE. (n.d.). https://www.aceee.org/topic/distributed-energy-resources#:~:text=Distributed%20energy%20resources%20can%20lead,risk%20of%20brownouts%20and%20blackouts.

Wood Mackenzie, Solar Energy Industries Association. 2024. US Solar Market Insight 2023 Year-in-Review. www.woodmac.com/industry/power-and-renewables/us-solar-market-insight/.

Documenting a Decade of Cost Declines for PV Systems. National Renewable Energy Laboratory. (2021, February 10). https://www.nrel.gov/news/program/2021/documenting-a-decade-of-cost-declines-for-pv-systems.html

U.S. Department of Energy (DOE). 2020. Energy Storage Grand Challenge: Energy Storage Market Report 2020. www.energy.gov/energy-storage-grand-challenge/articles/energy-storage-market-report-2020.