Marginal curtailment and the efficient cost of clean power

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Decarbonising electricity requires a massive increase in Variable Renewable Electricity (VRE), and in GB expanding the nuclear fleet. As the peak: average output ratio is high (in Britain, 2-4:1 for wind, 9:1 for PV), high VRE penetration implies that VRE will inevitably be curtailed (i.e. spilled or wasted). Earlier studies focused on the marginal curtailment of a single technology (e.g. wind). Most countries have various complementary VRE – solar PV with daily peaks, wind peaking in winter, while offshore wind experiences stronger more persistent wind. These different VREs interact, materially complicating economic analysis and policy design. This paper shows that an additional MW of any VRE technology (PV, on- or offshore wind) impacts the curtailment of other VRE, amplifying the marginal/average curtailment ratio (mc/ac). These interactions are critical in determining the social value of VRE investment and for choosing appropriate market and auction designs.

This paper uses data from the ESO (2024) *Future Energy Scenario Hydrogen Evolution* to simulate a notional 2030 target for GB and Europe. The findings reveal that the *mc/ac* ratio surpasses four under pro-rata curtailment due to cumulative factors. First, capacity factors for new 2030 VREs are considerably higher than the existing fleet, driven by technological advances (e.g. larger turbines). Each MW of 2030 VRE capacity increases output disproportionately, raising the mc/ac ratio. Second, VRE spillovers amplify total curtailment, reducing marginal capacity factors (potential capacity factor *less* marginal curtailment) and raising marginal costs.

VRE marginal costs depend on system flexibility and market interactions. Reducing average curtailment, whether through trade with unsaturated regions, storage, or demand-side response, disproportionately affects marginal curtailment and costs. Nuclear power can exacerbate VRE curtailment at higher penetration levels, but its emissions reduction is higher than the equivalent output delivered by VRE.

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This paper demonstrates the need to move beyond traditional Levelised Cost of Electricity (LCoE) metrics in evaluating VRE investments. We use a detailed Unit Commitment and Economic Dispatch (UCED) model to evaluate how trade, storage, and demand-side flexibility mitigate curtailment. High nuclear penetration can exacerbate VRE curtailment while increased EU VRE saturation reduces GB's VRE export potential, raising curtailment and reducing the benefit of more interconnection.

Market design is crucial in ensuring efficient VRE deployment, as metrics like LACoE (levelized average cost considering curtailment) and LMCoE (levelized marginal cost considering curtailment) may lead to different investment decisions than traditional metrics like LCoE. In GB, the latest (Round 6) Contract-for-Difference auction (Sep 2024) cleared at strike prices (£2023/MWh) at £67.09 (PV), £68.18 (onshore wind) and £72.65 (offshore wind) when the forward baseload wholesale electricity price in June 2024 was £77/MWh. The auctions pay on offered, not delivered output and so bids are based on the LCoE. The paper explores the implications of different cost measures for market and support design.

Without export and storage options, offshore wind's mc is 35.4%, compared to an ac of 6.3%, resulting in an mc/ac ratio of 5.7. The Levelised Marginal Costs of Electricity (LMCoEs) are significantly higher than LCoEs, with offshore wind's LMCoE reaching £92.06/MWh, more than double its LCoE (£43.04/MWh). Trade (exporting surplus VRE) is a key factor reducing marginal costs, lowering offshore wind's LMCoE to £50.36/MWh. However, storage provides only marginal additional benefit. Cost rankings remain consistent across scenarios (with or without trade, storage, etc.). Grid-scale PV offers the lowest cost, followed by offshore wind, onshore wind, and mid-scale (10-50 kW) PV. Efficient curtailment prioritises highercost technologies for curtailment, altering rankings to favour PV over wind technologies. The paper highlights the importance of auction design in accurately reflecting costs. The GB Contracts for Difference (CfD) fails to account for curtailment so bids reflect LCoEs. Unsubsidised merchant entry with pro-rata curtailment pushes investment decisions based on LACoE, about 10% higher than LCoE. Priority or efficient curtailment makes the LMCoE relevant, often 1.3 to 2.2 times higher than LCoE.