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Marginal curtailment under network constraints: evidence from the 2030 GB power system

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Chi Kong Chyong[1] and David Newbery[2]

Electricity markets in most countries are facing a rapid increase in Variable Renewable Electricity (VRE, wind and solar PV), both in their quest for decarbonisation and as the cost of VRE has fallen to be competitive with the carbon-adjusted cost of fossil generation. High VRE penetration inevitably leads to curtailment (shedding) as the cost of using surplus energy rapidly rises with volumes. Newbery and Chyong (2025) showed that investing in any single VRE (e.g. onshore wind) would lead to increased curtailment of other VREs (offshore wind, solar PV) as their time pattern of output varies. The effect is to magnify the marginal curtailment (the extra curtailment caused by an extra MW of VRE investment) above the level experienced in countries dominated by a single type (e.g. the island of Ireland with massive onshore wind penetration, Newbery, 2021). This paper goes further in demonstrating that VRE investment in zones within a country with limited boundary export capacity has spillover impacts on neighbouring regions, again amplifying marginal curtailment, raising the long-run marginal cost of that VRE.

Most countries have inherited transmission systems designed to deliver power from large fossil and nuclear stations to load centres. VRE is typically located in very different places and is often distant from demand. The result is a rapid increase in congestion at zonal boundaries, demands for new transmission links, and a growing urgency to provide better locational guidance for investment, dispatch, and balancing the system in real time. That was certainly a key motivation of the UK Government's consultation on the Review of Electricity Market Arrangements (REMA) in July 2022 (HMG, 2022). Congestion and the need for curtailing VRE is rising rapidly because of the under-appreciated fact that marginal curtailment is 3+ times average curtailment – the statistic that is usually reported. The paper provides additional evidence that marginal curtailment is even more significant where transmission is

[1] Oxford Institute for Energy Studies, 57 Woodstock Road, Oxford OX2 6FA. kong.chyong@oxfordenergy.org
[2] dmgn@cam.ac.uk, Faculty of Economics, University of Cambridge, Sidgwick Ave. Cambridge CB3 9DD.

inadequate for the new spatial patterns of generation investment, hence the urgency of improving locational guidance for that investment. The paper uses a detailed Unit Commitment and Economic Dispatch (UCED) model to evaluate how trade, storage, and demand-side flexibility mitigate curtailment within a zonal model of GB. It explores the impact of moving from the current GB system in which curtailment is ignored in determining payments to (contracted) VRE, to one in which GB is divided into seven zones defined by major boundary transmission constraints, and VRE contracts are modified to make VRE market responsive (as required by EU Regulation 2024/1747). Its central concerns are:

1. to estimate the additional curtailment resulting from recognising internal transmission constraints compared to those assuming the GB is a “copper plate” with no internal constraints, but only export limits
2. to measure marginal and average curtailments (mc, ac) with and without internal constraints,
3. to explore how cross-boundary flows of surplus VRE impact curtailment in different zones, and
4. to measure the appropriate average and marginal costs of investing in different VRE in each zone.

Average curtailment (*ac*) is normally measured by the fraction of potential output curtailed, which is the convention followed here. Marginal curtailment (*mc*) is similarly measured relative to potential output, i.e. the extra output (on average over a year) relative to the additional capacity that could potentially produce an average of 1 MWh over the year. Newbery (2021) showed that the marginal/average (*mc/ac*) curtailment ratio was typically above three for wind in the Single Electricity Market of the island of Ireland. In 2023-24, the UK-wide total (on- and offshore) *ac* rose from 5% to 9%. If the UK replicated the SEM, the *mc* would be 15-27% or more. One offshore wind farm (Seagreen) was curtailed 71% in 2024, despite receiving payments for its potential output, illustrating the potentially high ratio of *mc/ac*.

This paper demonstrates the need to move beyond traditional Levelised Cost of Electricity (LCoE) metrics in evaluating VRE investments. The levelised average cost (LACoE) is roughly equal to LCoE*PCF/ACF where P(A,M)CF is the Potential (Average, Marginal) Capacity Factor (e.g. 34% for onshore wind in 2030). PCF/ACF = 1/(1-*ac*) and PCF/MCF = 1/(1-*mc*) and these metrics are useful for computing relevant investment costs. Thus the long run marginal cost, LMCoE, is roughly LCoE/(1-*mc*) – and exactly that if variable costs are zero. The table below shows the results for expanding the potential output of a single VRE in each zone (taking one VRE at a time, e.g. expanding offshore wind in Z1 by 166 GWh/yr or by 0.88%).

		Z1	Z2	Z3	Z4	Z5	Z6	Z7	total	Copper Plate
mc p.c. of	OFF	34%	36%	17%	17%	16%	17%	17%	20%	26.1%
potential output	ON	48%	47%	21%	24%	23%	0%	14%	40%	18.1%
	PV	26%	26%	12%	10%	12%	17%	10%	12%	3.0%
PCF/MCF	OFF	1.52	1.56	1.21	1.21	1.19	1.20	1.20	1.25	1.35
1/(1-mc)	ON	1.91	1.87	1.27	1.32	1.29	1.00	1.16	1.66	1.22
	PV	1.35	1.36	1.14	1.11	1.14	1.21	1.11	1.14	1.03

Notes: OFF = offshore wind, ON= Onshore wind, Copper plate ignores all internal transmission constraints

The resulting long-run average and marginal costs are

Levelised average cost of VRE £2024/MWh

	Z1	Z2	Z3	Z4	Z5	Z6	Z7
OFF	£73.06	£58.73	£43.49	£37.02	£31.86	£38.43	£34.71
ON	£66.94	£53.13	£40.16	£35.05	£30.58	£35.76	£33.71
PV grid-scale	£75.36	£61.09	£44.41	£41.84	£34.32	£36.01	£34.18
PV mid-scale	£132.97	£115.35	£90.82	£89.79	£78.27	£76.95	£73.78

Levelised marginal costs of VRE £2024/MWh

	Z1	Z2	Z3	Z4	Z5	Z6	Z7
OFF	£95.36	£83.64	£51.48	£44.16	£37.39	£45.87	£41.32
ON	£102.46	£84.74	£48.29	£43.67	£37.02	£35.73	£37.89
PV grid-scale	£93.87	£77.52	£50.05	£46.29	£38.91	£43.40	£37.97
PV mid-scale	£165.62	£146.37	£102.36	£99.35	£88.73	£92.74	£81.97

The UK Government publishes LCoEs for the range of currently plausible generation technologies that are used to guide expectations in capacity auctions and VRE CfD auctions. At present, grid-connected and offshore wind farms are offered firm access, meaning they will be compensated for their lost profit if they are constrained off. As such they will be guided by the LCoEs when bidding in the annual CfD auctions. The European Union now requires that CfD holders "should participate efficiently in the electricity markets" (EC Regulation 2024/1747, 41). One way this could be encouraged is to instead of offering CfDs that pay on offered, not metered amounts, to replicate the standard two-way CfD that pays on a pre-determined volume regardless of actual output. To preserve hedging this volume could be the day-ahead (or intraday) forecast VRE output. If this were combined with the EU model of not paying when wholesale prices fall to zero, then the relevant cost measure would be the LACoE. If in addition the fixed tenor CfD were replaced with a fixed hour CfD (e.g. 40,000 MWh/MW, Newbery, 2023), bidders would expect to recover their full (undiscounted) over the contract period, and somewhere between the LCoE and the LACoE would represent the relevant cost metric.

Finally, in judging where to offer VRE connection, NESO might better be guided by the LMCoE, and as a result massively discourage any VRE connecting in Scotland (Zones 1 and 2).

References

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