Cambridge Judge Business School

EPRG Working Paper EPRG 2608

Cambridge Working Paper in Economics CWPE 2638

Trading off capacity factors, location, storage, access charges and curtailment for renewable electricity

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Variable Renewable Electricity (VRE, on- and off-shore wind, solar PV) enjoys higher potential capacity factors in very different locations to conventional fossil and nuclear plant. In addition, high resource areas are often far from load centres with little local demand. Most countries initially ignored this disparity, as at low VRE penetration the existing networks may have had adequate capacity to absorb the VRE regardless of location. Perhaps as a result, and perhaps driven by the desire to increase VRE capacity to meet targets, location was largely ignored. Thus the UK's 2030 Clean Power Action Plan's "expectations for the 2030 capacities of key technologies at national and regional level ... means 43-50 GW of offshore wind, 27-29 GW of onshore wind, and 45-47 GW of solar power, …".

As VRE penetration rises, so in most countries does curtailment unless matched by transmission expansion. While some regions (Texas, China, and initially at least, Italy) have reduced curtailment by expanding transmission, most countries and regions have experienced rising curtailment. Earlier work showed that marginal curtailment rates were typically 3+ times average curtailment rates typically reported, so rising VRE will lead to rapidly increasing curtailment unless transmission is commensurately expanded. Recent large wind farms in Scotland have been curtailed 50% of the time and this doubles the cost of delivered power. Least system cost expansion requires co-optimising transmission and VRE investment and questions the relative attraction of building transmission to access areas of high VRE potential output compared to locating VRE near load centres with lower potential output.

The Action Plan's targets guiding auctions were for capacity. The VRE Allocation Round 6 (AR6) auction in 2024 allocated capacity and cleared at strike prices competitive with fossil generation. Capacity, rather than delivery, is further incentivised by the form of the auctioned Contracts-for-Difference (CfDs), which offer firm connection to the grid, that is, if the transmission system cannot accept the potential output (up to that specified in the CfD) the generator will be compensated at the strike price for the curtailed output (unless reference prices go negative). The burden of locational guidance falls entirely on transmission charges. Efficient charges should be based on the marginal cost of expanding the network, not, as at present by assuming the existing network can be incrementally expanded at the existing cost.

This paper examines the trade-off between locating VRE in high resource areas and the cost of the extra (i.e. marginal) transmission entailed in delivering that power to load centres. This article develops a novel closed-form solution to give formulae for the efficient balance of transmission expansion, renewables capacity and voluntary curtailment in a simplified model where VRE is distant from load. Given equilibrium in demand centres, the solutions are independent of market prices, depending only on cost and technology parameters. As co-locating battery electrical storage systems (BESS) to reduce the need for transmission capacity is increasingly adopted (e.g. the proposed 80 MW Crosbie wind farm in Scotland with a 50 MW Li-On battery) the paper considers co-locating BESS as a substitute for entry capacity.

The trade-offs are modelled algebraically with wind (Scotland's preferred VRE) that specifies (and pays for) a specified level of transmission entry capacity (TEC) to connect to the grid. The model has two nodes – the North (Scotland) is connected to the South with its demand centres and less favourable wind resources. The paper derives simple expressions for the optimal ratio of TEC, K, to installed wind capacity, V, the average capacity factor and the curtailment fraction.

Co-located BESS has access to zero-cost surplus wind, and is therefore more profitable than local grid-connected BESS, which is assumed to be commercially viable. It is also argued in the literature to be a substitute for exit capacity and that finding is proved to hold in this model.

The model is calibrated for GB assuming either that transmission can be expanded on-shore to relax the Scotland-England boundary constraint, or, at something up to 6-10 times the cost, via proposed subsea HVDC links. Optimal TEC, curtailment rates and available capacity factors are determined for each case, with very adverse results is the marginal expansion is subsea, to the point that locating wind in Scotland may not cover its costs. Efficient TEC charges should only be firm when available and charge the marginal transmission cost, much higher if requiring offshore links. Existing transmission charges can be grandfathered, allowing new connections to be based on realistic marginal expansion plans and costs, offering a long-term contract at that charge. Given adequate on-shore export capacity, Scotland remains attractive, but not if exports are constrained and less so if subsea links are required.

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Publication	May 2026