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High renewable electricity penetration: marginal curtailment and market failure under "subsidy-free" entry[1]

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David Newbery

Ambitious plans to decarbonize electricity require high levels of variable renewable electricity (VRE) generation: on- and off-shore wind and solar PV. The cost of VRE is now competitive with conventional generation (with a suitable carbon price) holding out the prospect of "subsidy-free" VRE entry. The world average capacity factor for onshore wind between 2013-17 was 23%. Offshore wind has a higher capacity factor at 40%. Northern Europe solar PV (above 50º N) averages 15% or less. The share of VRE in total annual generation will be determined by its average capacity factor, but the peak to average ratio is its inverse, thus 3-4:1 for on-shore wind, 2-2.5:1 off-shore, and 7-10:1 in N Europe, lower in the south.

At high VRE penetration (above 50%) peak output will exceed total demand (including exports and storage), and the resulting surplus must be curtailed (i.e. spilled or discarded). The paper shows that marginal curtailment, that is the number of hours the last MW of capacity is prevented from delivering, is typically more than three times average curtailment. Price signals for VRE investment are given by average, not marginal, curtailment, leading to potentially excess entry by merchant VRE, even if the usual market inefficiencies are corrected.

This paper emphasizes the implication of higher marginal than average curtailment of VRE for assessing the benefit of further additions. The main contribution is to identify a largely overlooked requirement that with low VRE is costless, but becomes costly once curtailment becomes unavoidable. The overlooked system integration cost is the need to provide adequate inertia. System inertia is costless with adequate controllable generation synchronously connected to the network, as spinning turbines provide inertia whenever they are exporting electricity. Non-synchronous generation (wind, solar PV and DC links) lack the natural inertia of a spinning turbine. Inertia is needed to even out fluctuations in demand and supply - if there is a sudden shortfall, then the system frequency starts to fall, and its rate of fall depends on how much power can be drawn from the inertia connected to the system. Systems are designed to ensure that frequency is kept within a narrow range (+/- 1%) and primary

[1] This is a largely rewritten, simplified but extended version of EPRG WP 2036

reserve capacity is kept ready to increase output before that limit is reached. The lower the system inertia, the more challenging it is to activate this replacement inertia in time. If the rate of change of frequency exceeds a critical level then generation and load will automatically disconnect, potentially leading to a system-wide black-out.

As the share of simultaneous non-synchronous penetration (SNSP) reaches a critical level, the System Operator must curtail non-synchronous generation to maintain adequate inertia. In future, new ways of providing synthetic inertia may be introduced, but even then, system stability still requires synchronous generation. This paper considers two system stability requirements -- for inertia, already discussed, and the need to provide fast-acting reserves to maintain demand-supply balance in the event of outages or line failures.

VRE at high penetration levels will inevitably lead to curtailment, either for system stability reasons, or more obviously because potential VRE supply exceeds total system demand (including export and storage options). The contention of this paper is that analytical and systems models have overlooked additional inertia costs, which can be significant as the quantification in the paper demonstrates - on the island of Ireland this cost of inertia can add 10-20% to the cost of wind investment.

“Subsidy-free” VRE entry requires correcting all market failures – that carbon costs are properly charged, innovative technologies are compensated for their external learning benefits, and electricity pricing into the grid reflects the social marginal cost of generation, cleansed of distortionary subsidies. The remaining element of good market design is to ensure the efficient entry (and type) of new generation. With an efficient energy-only market, or auctioned capacity payments, fossil entry can be left to market signals. The key new factor considered here is that once wind penetration is high enough to cause system-wide curtailment, additional wind imposes an additional cost not reflected in market prices, as the marginal curtailment is many times higher than the average curtailment that sets prices. This can be viewed as a "tragedy of the commons" -- freeloading on the inertial services that are required by the marginal entrant but experienced by all VRE. These extra costs reflect the cost of the share of dispatchable generation that is needed to supply the inertia, and is simplest to consider as an annual charge to levy at the time of new entry of VRE. Offsetting this corrective charge, the global learning externality (mostly reaped abroad, but internalized if other countries offer similar subsidies as a club payment, e.g. under the EU Clean Energy Package) might be 11-17% of annual fixed costs and therefore of comparable magnitude.