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High renewable penetration: a new "tragedy of the commons"[1]

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The first theorem of welfare economics states that with a full set of markets a competitive equilibrium is Pareto efficient provided consumers are non-satiated. A competitive equilibrium exists provided production sets are convex, including the boundary case of constant returns to scale. In particular, in a stationary constant returns world of risk-neutral price-taking agents (or adequate hedging opportunities) if we can find a competitive equilibrium it should be efficient (provided all externalities and public goods are properly priced).

The electricity industry seems an ideal model of a potentially competitive market. The service of electricity supply is homogenous (as the System Operator is charged to maintain quality of service within very tight limits). In mature liberalized markets like the U.S. Standard Market Design and the EU Integrated Electricity Market producers (generators) offer supply functions while retailers and large customers offer their demand functions into auctions. The auctions clear to determine prices at each node (in the U.S.) or zone (in the EU) for each time period, simulating the Walrasian auctioneer in a way unseen in almost all other markets.

For an electricity industry in long-run equilibrium with a sufficient fraction of controllable generation it is a standard result that the equilibrium will be efficient. The electricity market model of this article has all the obvious externalities properly internalized. It has a socially optimal carbon price, all other damaging externalities are properly priced or prohibited, and, critically, renewable generation is assumed competitive against conventional (fossil) generation. Variable renewable electricity (VRE) like wind has a peak to average output ratios of 3-4:1. Above a certain level of penetration, wind will inevitably be in surplus some of the time, as it will be excessively expensive to store or export all the surplus. In such cases the System

[1] This paper is a shorter and simpler version of "Club goods and a tragedy of the commons: the *Clean Energy Package* and wind curtailment" (EPRG 2036) dated 31 December 2020.

Operator must curtail some fraction of total wind to balance supply and demand. In the market studied here, when wind is surplus the market price falls to its avoidable cost, taken as zero. When the price falls to the avoidable cost all surplus wind will voluntarily self-curtail (i.e. reduce output) until supply and demand are matched, at which price all wind will earn zero profits.

The surprising and novel claim in this article is that even if all externalities are properly priced and the industry is in a free-entry long-run price-taking equilibrium, once the share of VRE (wind) reaches a critical level at which (self-)curtailment occurs, the resulting competitive equilibrium will be inefficient without additional taxes or charges. There is a mismatch between the social and market value of wind investment. The social value depends on the *marginal* curtailment caused by the additional investment, which is 3-4+ times the *average* curtailment. Consequently, free entry will result in too much VRE, as all wind turbines will equally make profits in non-curtailed hours, and all make zero profit in curtailed hours. As entry will be driven by *average*, not *marginal* profit, there is a “tragedy of the commons”, akin to free entry of grazing cattle on the common pasture. In this case the pasture is the number of profitable hours of operation.

As there is a considerable difference in the avoidable cost of non-VRE and VRE generation, the move from uncurtailed to curtailed periods represents a step change in efficient prices, not a marginal change that is more typical of conventional markets. However, this is not the main reason, as there is no inefficiency with nuclear power with zero short-run avoidable costs. Efficient volumes of VRE therefore requires properly charging for access to these high value hours through some form of entry levy.

The paper sets out a simple model to show the source of this unpredictability cost and points to the deficit between social value that depend on marginal curtailment and market revenue that is only reduced by average curtailment. It derives the formulae for the charges needed in a liberalized market to deliver the desired level of renewables penetration and estimates their magnitude. The estimates provided in this paper suggest that the entry tax is material and could range from 10-20% of the annual fixed cost of on-shore wind, if anything larger than the learning externalities calculated in the more complex model provided in EPRG WP 2036, which draws on data from the Single Electricity Market (SEM) of the island of Ireland. The SEM is a particularly important market to study, as it is widely recognized as being at the forefront of addressing the challenge of high VRE penetration in a small, isolated system.