Game-theoretic Modeling of Transmission Line Reinforcements with Distributed Generation

(Extended Abstract)

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ABSTRACT

Favourable sites for renewable generation are often remote locations (such as islands) where installed capacity, e.g. from wind turbines, exceeds local aggregate demand. We study the effect that curtailment mechanisms - applied when there is excess generation - have on the incentives to build additional capacity and the profitability of the generators. Next, for a two-location setting, we study the combined effect that curtailment schemes and line access rules have on the decision to invest in transmission expansion. In particular, for "common access" rules, this leads to a Stackelberg game between transmission and local generation capacity investors, and we characterise the equilibrium of this game. Finally, we apply and exemplify our model to a concrete problem of a grid reinforcement project, between Hunterston and the Kintyre peninsula, in western Scotland, and we determine a mechanism for setting transmission charges that assures both the profitability of the line and local renewable investors.

Keywords

generation incentives, renewable energy, transmission investment, Stackelberg game

1. INTRODUCTION

Integrating energy generated from renewable sources into existing grids is one of the key challenges for ensuring a sustainable, carbon-free energy future [1, 5]. A plethora of incentives have led fast increases of installed renewable generation capacity. However, a key problem is that locations which are best suited for installing new generation capacity (due to favourable resources or social approval), such as large wind turbines, are typically remote locations, such as islands far from population/industry centres of high electricity demand. At these areas, a substantial amount of generated energy might be subject to *curtailment*, as it cannot be absorbed by the grid, because of low local demand or insufficient grid capacity to transport it elsewhere. In practice, each location's curtailment level and crucially the curtailment policy applied are very significant factors affecting the decision of investors to build new generation capacity [4]. Apart from technical, regulatory and legal implications, covered by the power systems literature [3], the curtailment schemes can play a crucial role in generation and transmission expansion, the study of which is the prime objective of our work.

Integration of renewable generation requires substantial transmission investment, traditionally performed by distribution network or transmission system operators (DNOs/ TSOs), often associated with prohibitive costs. For this reason, incentivising privately built lines [2] would be highly desirable from a public policy standpoint. New power lines could be built under a *"common access"* principle, where private line investors are required to allow access to third parties, by setting a payment mechanism per unit of energy transmitted, the level of which is subject to a cap set by the regulator. In this work, we use game-theoretical models to examine the interplay of curtailment mechanisms and line access rules and we show this leads to a complex *Stackelberg game*, between the line investor and local generators, and we determine the expected generation and profits at equilibrium. Finally, we apply our theoretical results to a real-life project.

2. CURTAILMENT STRATEGIES AND GENERATION INCENTIVES

The most widely used curtailment schemes can be summarised as last-in-first out (LIFO) and Pro Rata schemes. In *LIFO*-based curtailment, generators are curtailed based on the inverse order in which they were granted the right to connect to the grid. By contrast, *Pro Rata* shares curtailment equally among installed generators proportionally to the rated capacity or actual power output, at the time of curtailment. Our work shows that LIFO displays a clear market advantage for early connections, leading to lower capacity factors for "late" generators than Pro Rata, which is detrimental both for the viability of existing and future investment. Given an area where curtailment is imposed, we determine an upper level of tolerable curtailment, which enables renewable capacity investment to be profitable, which depends on the relation of the generation cost with the Feed in Tariff (FiT) price. Moreover, since the curtailment scheme is usually chosen by a regulatory authority or the local DNO, we show that given a single location and a perfectly competitive setting (Cournot analysis), the local generation capacity is maximised under proportional curtailment schemes, which share curtailment equally amongst generators.

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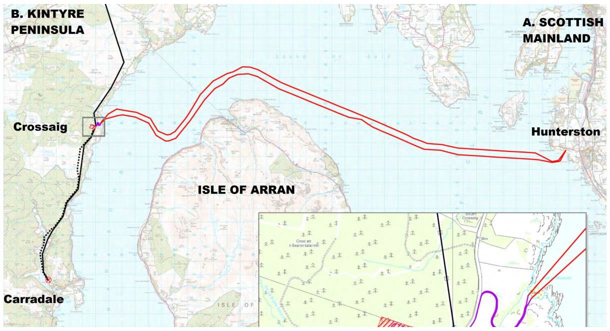

Figure 1: Transmission line connecting Scottish mainland to the Kintyre peninsula

3. TRANSMISSION INVESTMENT

Next we consider two locations, where excess generation and demand are not co-located: location A is a net consumer (e.g. a mainland location with industry or significant population density) and B is a net energy producer (e.g. a remote region rich in wind resource). Moreover, we consider two players: a line investor interested in building the $A - B$ transmission link and additional renewable generation capacity at B and a local player, who represents other renewable generators or investors located at B.

Crucially, in this setting, the line investor has a "first mover" advantage, as only he can build the grid infrastructure, which is expensive and technically challenging and only a limited set of investors (such as DNO-approved or DNOs themselves), have the technical expertise and regulatory approval to carry it out. The line investor (or leader) can assess and evaluate the reaction of other investors to determine his strategy, namely the capacity of the power line and the level of renewable capacity to be installed, with ultimate goal to influence the equilibrium price and maximise his profits. Local investors (or follower) can only act after observing the leader's strategy. This two-stage process is analysed as a Stackelberg game and its equilibrium is found through backward induction. We determine the expected generation and profits for both players, for LIFO and Pro Rata. Equilibrium results depend on the FiT price, transmission fee, generation costs and the demand at A. We show that under a LIFO scheme the line investor is protected from any curtailment, hence he can build all generation capacity to cover demand at A himself. On the other hand, a proportional scheme leads to larger volumes of generation capacity being built than actual demand, subject to an upper level of curtailment.

4. NETWORK UPGRADE CASE-STUDY

Next, the theoretical model was applied to the concrete case-study of the Kintyre-Hunterston transmission link, in Western Scotland[1] (see Fig. 1). The power grid in the Kintyre peninsula, originally designed to serve a rural area, proved insufficient to accommodate the large amounts of wind generation built in the area. SSE (the local DNO) proceeded in a $\pounds 230m$ network upgrade project, which includes a sub-sea link, creating headroom for additional 150 MW of renewable capacity. Based on the parameters of this project, we determine the capacity built and the profits of the line and local investors for a Stackelberg game.

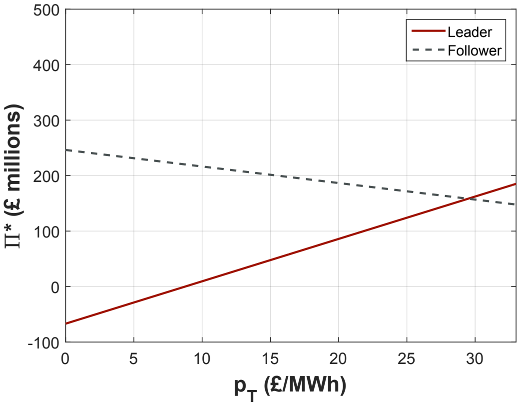

Figure 2: Effect of transmission fee on profits at Stackelberg equilibrium

In Fig. 2, we show the effect of the transmission fee p_T on the profits Π of the players. The transmission charges, agreed by the line investor and the regulatory authority, have to be set within a specific range. Low values of p_T may lead to the investment being aborted (i.e. when the leader's profits are above 0 – in our case, transmission charges need to be at least $\pounds 0.08/kWh$) and high values might discourage additional investment from local community investors. Regulatory authorities, who seek renewable facilitation can promote grid infrastructure expansion, not only by providing subsidies or technical support, but by allowing "common access" rules, as a tool to attract private investment and improve the profitability of line investors. To our knowledge, this is the first work examining the combined effects of curtailment strategies and transmission access rules on generation capacity investment and foremost network expansion.

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