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Game-theoretic Modeling of Curtailment Rules and their Effect on Transmission Line Investments

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Abstract—This paper provides a study of the impact of curtailment schemes, applied when generation exceeds demand, on the Capacity Factor (CF) of wind generators, including the effect of spatial wind correlation among different locations. Moreover, we discuss how a round-robin curtailment rule could be implemented to guarantee approximately equally curtailment ratio for generators of unequal rated capacity. Next, we consider a two-location problem, where excess renewable energy generation and demand are not co-located. We study the combined effect that curtailment schemes and line access rules have on the decision to invest in new transmission lines. In particular, we show that, for *common access* rules, this can lead 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 building a transmission link in western Scotland, and we propose a mechanism for setting transmission charges that assures both that the transmission line gets built, but investors from the local community can also benefit from investing in renewable energy.

I. INTRODUCTION

Integrating energy generated from renewable energy sources (RES) into existing grids is one of the key factors for ensuring a sustainable, carbon-free energy future [1], yet sets a new set of challenges to electricity networks [2]. A key problem is that locations which are best suited for installing new capacity due to favourable resource conditions or social approval, e.g. large wind turbines, are typically remote locations (such as windy islands), situated far from population/industry centres. Hence, a lot of new RES capacity installed is subject to *generation curtailment*, a strategy where distributed generators are granted non-firm grid access and are required to adjust their outputs according to the system operator's instructions, foremost due to network constraints, low local demand or insufficient distribution or transmission network capacity.

Technical and regulatory aspects of curtailment have been extensively studied [3], however, it is becoming increasingly clear, that especially in areas of network congestion, each location's curtailment level (and the curtailment policy applied) can play a crucial role on the total installed generation capacity, due to their effect on investor decisions [4] and might therefore discourage future RES investment.

The long term solution is to build or reinforce transmission and distribution lines, between remote and areas of high demand. Network upgrade often presents prohibitively high costs and is traditionally performed, or partially supported by public investment means, usually through the transmission system or local distribution network operator (TSO/DNO). From a public policy standpoint, it would be highly desirable to incentivise private investors to undertake part of the required grid infrastructure investment. An approach would be that power lines are built under a *common access* principle, where the line investors may be given a license under the obligation to allow line access from third parties, subject to a transmission fee per unit of energy transported, the level of which is subject to a cap set by the regulator. The interplay between curtailment rules and principles of access applied to power lines, raises potentially complex issues, especially as the line investor, regulator and local RES investors may have different underlying goals [5]. In this paper, we use the tools from game theory to examine these interactions and show that a complex *Stackelberg game* can occur, in which the decision to build a transmission line depends on the equilibrium strategy of local investors to invest in additional generation capacity.

Various commercial and academic studies [3], [4], [6], [7] discuss the application of curtailment strategies, primarily focusing on their technical, legal and regulatory implications, rather than their impact on investor's decision-making, regarding generation or transmission assets, which is the focus of our work. In the context of deregulated electricity markets, transmission planning techniques need to adopt optimisation [8] and strategic modeling of market participants [9], as opposed to 'intuitive' approaches, adopted by utility companies in the past [10]. This is where game theory tools can play a significant role. Strategical behaviour of energy investors has been simulated, with agent-based modeling [11], [12], or by examining alternative market structures, where network upgrade is performed by system operators or private investors, leading to different optimal results [13]. In [14], coalition formation is used to coordinate privately developed power grid lines, in order to reduce inefficiencies and transmission losses, while transmission planning and expansion at areas of network congestion were studied in [15]. Curtailment strategies or line access rules were not considered in these works. However, as the profitability of any scheme is directly affected by such rules, we focus on this factor for our work.

Stackelberg games have been used to model transmission upgrade, using economic analysis with social welfare [16], Locational Marginal Pricing [17] or highlighting the uncertainties of RES generation [18]. Recent works on the renewable energy

domain, use Stackelberg game analysis to describe energy trading of microgrids [19], [20] or propose novel funding schemes for RES investment [21].

In summary, the contribution of this work to the state of the art can be stated as follows:

- First, we formalise the effect of commonly-used curtailment rules on the RES capacity installed at a particular location. We show that the resulting capacity built and profitability of different generators can differ widely under different curtailment models or wind correlation, and we propose a new round-robin rule.
- Second, we study the network upgrade as a Stackelberg game between the line and local RES investors, for common access rules, and we derive the amounts generated and profits in the equilibrium of this game.
- Finally, we exemplify our analytical results for the case of a grid reinforcement and the financial parameters of the Kintyre-Hunterston link, in the UK, and determine a feasible range of the transmission charges.

The remainder of this paper is organised as follows: Section II elaborates on curtailment strategies. Effects on transmission investment are shown in Section III. Numerical results of a line upgrade case-study are presented in Section IV, while Section V concludes.

II. CURTAILMENT STRATEGIES

The selection of a curtailment strategy (see [7], [22] for an extensive review) needs to account for several assessment criteria, such as fairness, transparency, efficiency or reliability. The schemes proposed take into consideration: the technical characteristics of the generators, their size, location, expected response time, and crucially, the order of connection to the power grid. In this paper, we focus our attention to the main mechanisms found in the literature or applied to commercial Active Network Management (ANM) schemes[1]:last-in-first-out (LIFO), Pro Rata (or proportional) and Rota. In *LIFO*-based curtailment, generators are curtailed based on the inverse order in which they were granted the right to connect to the distribution network. By contrast, *Pro Rata* shares curtailment equally among installed generators, proportionally to the rated capacity or actual power output at the time of curtailment. Finally, *Rota* curtails generators at a rotational basis or a predetermined rota, as specified by the system operator.

To illustrate the effects and operation of these schemes, we consider a simple network of three wind generators of $P_{N_1} = 7$ MW, $P_{N_2} = 2$ MW and $P_{N_3} = 3$ MW rated capacity, where the subscript denotes the chronological order of their connection to the power grid. For simplicity, we assume there is no export capability and the demand is constant and equal to $P_{D,t} = 6$ MW, $\forall t$. For a given time interval t, if all generators are producing their nominal output power, a total of $P_{C,t} = 6$ MW needs to be curtailed. The allocation of this

power to the generators depends on the scheme selected: With LIFO, the third and second generator are completely curtailed and the first is curtailed by 1 MW. On the other hand, when Rota is implemented, the generators take turns, resulting here in the first generator being curtailed by 6 MW, while the other generators are not affected. In the next curtailment event, the second generator is required to be curtailed and so on. By contrast, with Pro Rata the allowed export is allocated proportionally to the generator's output, resulting in 3.5 MW, 1 MW and 1.5 MW curtailed power, respectively.

If *Pro Rata* is not always desirable (technically speaking, it may require modified pitch-controlled wind turbines, such that their output can be adjusted as needed, which may be more expensive), we can think of an equivalent Rota-type strategy with the same 'fairness' properties, a strategy we call *Fractional Round Robin* (FRR). With FRR, the power curtailed is distributed sequentially on a rotation basis, according to the number of rated capacity units installed, so that larger generators are chosen proportionally more times, in direct relation to their size. This means for instance that, on average, every 12 times a curtailment of 6 MW is needed, the first generator will be curtailed 7 times, the second 2 times and the third 3 times. Being aware in advance of the curtailment order, the uncertainty of short-term power output prediction of a generator can be reduced. Moreover, for a sufficiently long period of time (i.e. many years, the typical lifetime of a wind turbine), the curtailment rate under FRR converges to the proportional curtailment rate with Pro Rata.

We implement a simulation process, in the course of one year, to compute the capacity factors of the wind generators, under different schemes. However, since network constraints are usually applicable to a particular geographical area of the grid, where wind conditions may be similar, the power output of the generators presents a level of spatial correlation, which is significant for the required curtailment level at this area. To model correlation, we apply the technique developed by Früh (2015) [23]. First of all, we generate 8760 data points of wind speed $u_{rand,i}$ for $i = 1...3$ generators, from three *random* and independent samples of a Weibull distribution (one for each generator), using the typical UK values of $c = 9$ m/s and $k = 1.8$. We set the wind speed at the first generator's location as a reference u_{Ref} and we produce random, yet cross-correlated wind data series u_i at each generator's location, by the following equations:

$$u_i(t) = c_r \cdot u_{Ref}(t) + (1 - c_r) \cdot u_{rand,i}(t) \qquad (1)$$

$$c_r = \frac{1}{\pi} \cdot \arccos(1 - 2r) \qquad (2)$$

where r is the Pearson's correlation coefficient. The data series are then converted to power outputs, using a generic model of a wind turbine[2]. If the aggregate power at time t exceeds the power demanded, then curtailment is required, which is allocated to the generators according to the strategy imposed.

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[1]LIFO is used in: https://www.ssepd.co.uk/OrkneySmartGrid/ and www.ninessmartgrid.co.uk/our-project/
Pro Rata is used in: http://innovation.ukpowernetworks.co.uk/innovation/en/ Projects/tier-2-projects/Flexible-Plug-and-Play-(FPP)/

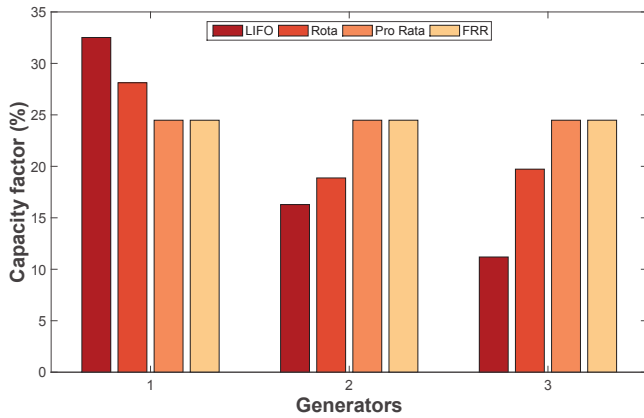[2]Based on the power curve of Enercon E44 commercial wind turbine.

Fig. 1. Curtailment mechanisms effects on the CF of wind generators under LIFO, Rota, Pro Rata and FRR

Fig. 2. Fairness under different curtailment schemes

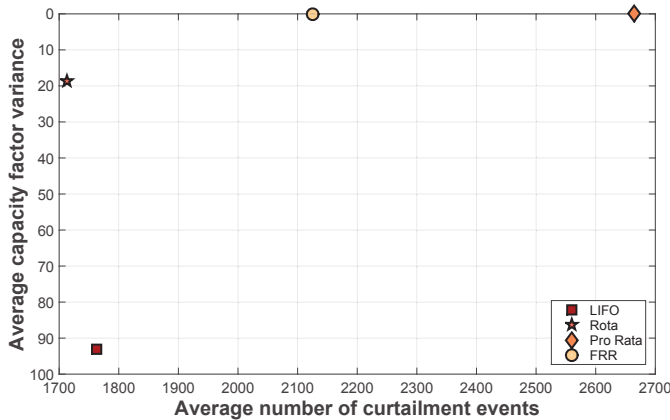Fig. 3. Correlation effects on average CF under different curtailment schemes

Fig. 1 shows the CF results for each generator under the four different schemes for conditions of perfect correlation ($r = 1$). LIFO clearly favours 'early' connections, while the third generator suffers a reduction of 67.4%. Rota can disadvantage smaller-sized generators. On the contrary, Pro Rata produces equal CF reduction for all generators, while FRR produces similar results to Pro Rata, as expected.

A measure of fairness is the variance of the average CF for each strategy. In Fig. 2, we illustrate, for $r = 1$, this variance with the average of the number of curtailment events required. LIFO presents a poor performance with respect to fairness, as opposed to Pro Rata, which requires the largest number of curtailment events. FRR can present similar fairness properties to Pro Rata, while reducing significantly the number of curtailment events per generator. Finally, Rota is fairer than LIFO and requires the smallest number of curtailment events compared to all schemes.

Finally, as shown in Fig.3, the required total curtailment increases, as we proceed from no correlation to perfect correlation, resulting in lower CFs.

In the following section, we turn our attention to modeling the grid infrastructure investment, at areas where generation curtailment is applied.
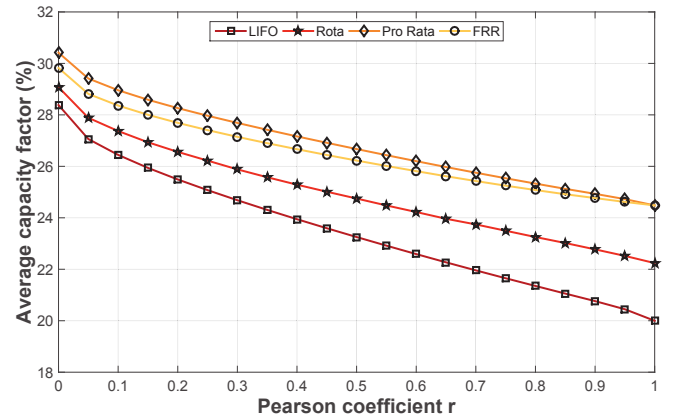
III. CURTAILMENT & NETWORK UPGRADE

Here, we study how the applied curtailment influences the decision to build or reinforce transmission lines.

We consider two locations: A is a net consumer (where demand exceeds supply, e.g. a mainland location with industry or significant population density) and B is a net energy producer (favourable RES conditions, e.g. a remote region rich in wind resource). In practice, there would be some local demand and supply, considered here negligible, and installation of new RES capacity is not be feasible without a network upgrade. Location A has a net demand of $E_{D,A}$, equal to local demand minus local generation.

Moreover, we consider two players: the line investor, who can be merchant-type or a utility company and is building the $A - B$ interconnection and possibly renewable generation capacity at B, equal to $E_{G_1,B}$, and a local player, who represents the local RES generators or investors located at B, $E_{G_2,B}$. This second player can be thought of as investors from the local community, who do not have the technical/financial capacity to build a line, but may have access to cheaper land, find it easier to get community permission to build turbines etc., hence may have a lower per-unit generation cost[3]. Essentially, E_{G_i} represents the expected energy units, for the project lifetime, according to the resource on the site's location, without encountering curtailment. Note that, while for a particular time period, such as an hour or a day, the expected generation is uncertain, for the overall lifetime of a RES project, it can be estimated with relatively high certainty from the weather and wind patterns at this location.

For simplicity, we assume there is no RES capacity installed at location B prior to the construction of the power line. However, the decision of building the power line will elicit a reaction from local investors. This two-stage process is analysed as a Stackelberg game. Crucially, the line investor

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[3]Note that in Scotland, or other countries such as Denmark, local groups often act together to make land available and invest in RES projects. Community Energy Scotland (CES) is an umbrella organisation of such groups.

has a *first mover* advantage, as only he can build the grid infrastructure, which is expensive, technically challenging and only a limited set of investors (e.g. DNO-approved) have the expertise and regulatory approval to carry it out. The power line cost is estimated as $C_T = I_T + M_T$ over the project lifetime, where I_T is the cost of building the line (or initial investment) and M_T the cost of operation and maintenance. The monetary value of the power line is proportional to the energy flowing from B to A, charged under common access rules with p_T transmission fee per energy unit. Moreover, the cost of expected generation per unit c_{G_i} (for constant depreciation) is $c_{G_i} = (I_{G,i} + M_{G_i})/E_{G_i}$, where I_{G_i} the cost of building the plant and M_{G_i} the operation and maintenance costs, and we assume that the energy generated by a RES unit is sold at a constant feed-in-tariff price (FIT), equal to p_G.

The line investor or *leader* can assess and evaluate the reaction of other investors to determine his strategy (i.e. the line and RES capacity to be installed), aiming to influence the equilibrium price. Local generators or *followers* can only act after observing the leader's strategy. The equilibrium of the game is found by *backward induction*. First, the leader estimates the best response of local generators, given its own output and then decides his strategy aiming to maximise his profit. At a second stage, the follower observes this strategy and decides his generation capacity, as his best response, i.e. maximising his own profit, as anticipated by the leader.

The network access arrangements play here a crucial role for the market equilibrium formed. Hence, we define a new parameter, which quantifies the curtailment imposed to each generator. If the expected curtailed energy units are E_{C_i}, then the curtailment rate CR_i of i generator, is defined as the ratio of expected curtailment to expected generation, over the project lifetime $CR_i = E_{C_i}/E_{G_i}$ and it is crucial for the viability of existing and future RES investment. Here, $0 \leq CR_i < 1$ and can be interpreted as CF reduction, e.g. $CR_i = 5\%$ results in a 5% CF reduction. Next, we focus and present the equilibrium results for LIFO and a fair curtailment scheme, which can be an expression of either Pro Rata or FRR.

A. LIFO scheme

Under a LIFO scheme, the leader is protected from any curtailment, hence he can build all generation capacity to serve $E_{D,A}$ himself and maximise his profits. The local investors have to provide all curtailment required, as *late* connections, thus there is no incentive for them to invest in new capacity.

Lemma 1: The transmission investment game between the line investor and local generators with LIFO curtailment results in the expected generation and profits, at Stackelberg equilibrium:

$$E_{G_1,B}^* = E_{D_A} \tag{3}$$
$$E_{G_2,B}^* = 0 \tag{4}$$
$$\Pi_1^* = (p_G - c_{G_1}) \cdot E_{D_A} \tag{5}$$
$$\Pi_2^* = 0 \tag{6}$$

Proof: The capacity of the transmission line is bound by the demand at mainland, therefore total generation capacity

at location B, $(E_{G_1,B} + E_{G_2,B})$ cannot exceed E_{D_A}. Any generation capacity built exceeding the demanded energy, has to be curtailed. Taking this into account, the profit functions of the two players are

$$\Pi_1 = p_T \cdot E_{D_A} + (p_G - p_T - c_{G_1}) \cdot E_{G_1,B} - C_T$$
$$\Pi_2 = (E_{D_A} - E_{G_1,B}) \cdot (p_G - p_T - c_{G_2})$$

Accounting for the leader's market advantage, we derive the desired equations. ∎

B. Pro Rata or FRR scheme

The main difference from LIFO, is that proportional rules are imposed to all generators, regardless of their order of connection. Therefore, more total capacity $E_{G,B} = E_{G_1,B} + E_{G_2,B}$ than the energy demanded at A can potentially be installed, as long as the curtailment rate or energy curtailed $E_{C,B} = E_{G,B} - E_{D,A}$ allows for the investments to be profitable. The curtailment rate at location B is given by

$$CR_B = 1 - \frac{E_{D,A}}{E_{G_1,B} + E_{G_2,B}} \tag{7}$$

Given this, the general profit functions of the players, which are functions of both players energy outputs $\Pi(E_{G_1,B}, E_{G_2,B})$, can be expressed as:

$$\Pi_1 = \left(\frac{p_G \cdot E_{D,A}}{E_{G_1,B} + E_{G_2,B}} - c_{G_1} \right) \cdot E_{G_1,B}$$
$$+ \frac{p_T \cdot E_{D,A}}{E_{G_1,B} + E_{G_2,B}} \cdot E_{G_2,B} - C_T \tag{8}$$

$$\Pi_2 = \left[\frac{(p_G - p_T) \cdot E_{D,A}}{E_{G_1,B} + E_{G_2,B}} - c_{G_2} \right] \cdot E_{G_2,B} \tag{9}$$

Before stating our main Stackelberg equilibrium results, we need to define the players' best responses.

Proposition 1: Given the output of the leader $E_{G_1,B}$, the follower's best response is:

$$E_{G_2,B}^* = \sqrt{\frac{(p_G - p_T) \cdot E_{D,A} \cdot E_{G_1,B}}{c_{G_2}}} - E_{G_1,B} \tag{10}$$

Proof: Let the value of $E_{G_2,B}$, which maximises the profit of the follower, be $E_{G_2,B}^* = \underset{E_{G_2,B}}{argmax} \Pi_2$. Setting as zero the partial derivative of Π_2 in (9), with respect to $E_{G_2,B}$ and rearranging, we get (10). ∎

Proposition 2: Given the output of the follower $E_{G_2,B}^*$, the leader's best response is:

$$E_{G_1,B}^* = \frac{(p_G - p_T) \cdot c_{G_2} \cdot E_{D,A}}{4 \cdot c_{G_1}^2} \tag{11}$$

Proof: Let the value of $E_{G_1,B}$, which maximises the profit of the follower, be $E_{G_1,B}^* = \underset{E_{G_1,B}}{argmax} \Pi_1$. Substituting (10) in (8) and then setting as zero the partial derivative of Π_1 with respect to $E_{G_1,B}$ gives the stated expression. ∎

Lemma 2: The transmission investment game between the line investor and local generators with a proportional scheme

results in expected generation and associated profits, at Stackelberg equilibrium:

$$E^*_{G_1,B} = \frac{(p_G - p_T) \cdot c_{G_2} \cdot E_{D,A}}{4 \cdot c_{G_1}{}^2} \quad (12)$$

$$E^*_{G_2,B} = \frac{(p_G - p_T) \cdot (2 \cdot c_{G_1} - c_{G_2}) \cdot E_{D,A}}{4 \cdot c_{G_1}{}^2} \quad (13)$$

$$\Pi_1{}^* = \frac{(p_G - p_T) \cdot c_{G_2} \cdot E_{D,A}}{4 \cdot c_{G_1}} + p_T \cdot E_{D,A} - C_T \quad (14)$$

$$\Pi_2{}^* = \frac{(2 \cdot c_{G_1} - c_{G_2})^2 \cdot (p_G - p_T) \cdot E_{D,A}}{4 \cdot c_{G_1}^2} \quad (15)$$

Proof: Replacing Prop. 2 in (10), the optimum output of local generators $E^*_{G_2,B}$ is found, i.e. (13). Finally, substituting the energy outputs at equilibrium (12) and (13), in (8) and (9), we derive the equilibrium profits $\Pi_1{}^* = max \; \Pi_1$ and $\Pi_2{}^* = max \; \Pi_2$. ∎

Finally, note that this strategic interaction requires the total generation capacity to exceed the demand at A, i.e. $E_{G_1,B} + E_{G_2,B} > E_{D,A}$. This constraint yields the following conditions, which must hold for the setting to actually be game-theoretic (and for our analysis to be relevant):

$$c_{G_2} < p_G - p_T \quad (16)$$

$$c_{G_1} < \frac{p_G - p_T}{2} \quad (17)$$

IV. CASE STUDY

In this section, we apply the theoretical framework of the Stackelberg game with Pro Rata (c.f. Lemma 2) to the concrete case-study of Kintyre-Hunterston grid reinforcement project[4], currently under development in the UK. Grid infrastructure in the Kintyre peninsula was originally designed and built to serve a typical rural area of low demand. Wind generation rapid growth, due to substantial incentives, quickly led to high volumes of renewable investment in the region. RES capacity was expected to reach 454 MW by the end of 2015, and future connections estimations exceed 793 MW. The necessity for large transmission investment soon became apparent, therefore the local DNO proceeded in a £230m network upgrade project connecting existing Hunterston substation, partially through a sub-sea link to Crossaig, thus creating headroom for additional 150 MW renewable capacity estimated to provide a net lifetime benefit of £520m [24]. Based on these project figures, we consider a simplified two-node network, in which the energy demand in the mainland, met by generation in Kintyre, equals the energy transmitted through the power line. With the majority of investment being wind projects, we estimate the total energy demand as $E_{D,A} = 9,855,000$ MWh for 25 years project lifetime. As currently valid in UK for medium size wind projects, the FIT price was set to $p_G = £82.60/\text{MWh}$.

In Figure 4, we summarise the results of our model, namely the generation capacity built and associated profits at Stackelberg equilibrium, for three scenarios: *Scenario 1* corresponds to the plots of the first column and shows the effect of varying the local investors' generation cost, keeping all other parameters at constant values (set as $c_{G_1} = p_T = 0.3p_G$ and

[4]https://www.ssepd.co.uk/KintyreHunterston/

$c_{G_2} = 0 \dots c_{G_1}$), *Scenario 2* in the second column shows the effect of varying the line investor's generation cost (with settings: $c_{G_2} = p_T = 0.3p_G$ and $c_{G_1} = 0.125p_G \dots 0.35p_G$) and *Scenario 3* in the third column shows the effect of varying the transmission fee (with other parameters set at $c_{G_1} = 0.3p_G$, $c_{G_2} = 0.9c_{G_1}$ and $p_T = 0 \dots 0.4p_G$). For each scenario, the range of the 'free' parameter (fixing the others) is determined from the constraints in (16) and (17).

Given a certain FIT (this parameter is controlled by the regulatory authority), the line investment feasibility depends directly on the generation cost c_{G_1} and transmission fee p_T. If the line is built, it sets up a level of total feasible generation investment at B which, combined with Pro Rata access rule, leads to larger volumes of capacity being built than actual demand (see 1st row of Fig. 4), as long as the curtailment rate is kept under reasonable levels. Note the level of total generation does *not* depend on the generation costs of local investors, since they cannot act without the existence of the line (see Fig. 4 1st row, 1st column). For all settings, the size of c_{G_2} relative to c_{G_1} determines how exportable level of generation capacity is shared. Cheaper generation has an advantage in all 3 sets of results (c.f. Fig. 4 first row), although as the graphs show, the dependency is not necessarily linear.

Another conclusion is that transmission charges, agreed by the line investor and an independent regulatory authority, has to be set within a specific range. Low values of p_T may lead to transmission investment being aborted, somewhat larger values might theoretically be sufficient to achieve profitability for the line investor, however, hide the risk of 'free-riding' from local investors, who benefit from the leader's investment at cost much less than to leader's himself. What the result in Fig. 4 (row 2, col. 3) shows is that there exists a range in which p_T can be set such as to assure the line gets built (i.e. when the leader's profits are above 0 – in our case, transmission charges need to be at least £8/MWh), but also not discourage other local renewable investors.

V. CONCLUSIONS & FUTURE WORK

To our knowledge, this is the first work examining the combined effects of curtailment strategies and transmission access rules on RES capacity investment and network expansion. Our research focused on the effects of the curtailment schemes to investment decisions and market behaviour. We model grid reinforcement, as a two-stage strategic game between the line investor and local generators and determine generation capacities and profits at equilibrium. Based on a UK grid reinforcement project, we propose a method to calculate transmission charges, under common access rules, which enables the implementation of both transmission and local generation investments.

Future work includes expanding the developed two-location model to more complex settings and multiple locations. We also plan to expand the equilibrium results to settings with partial correlation.
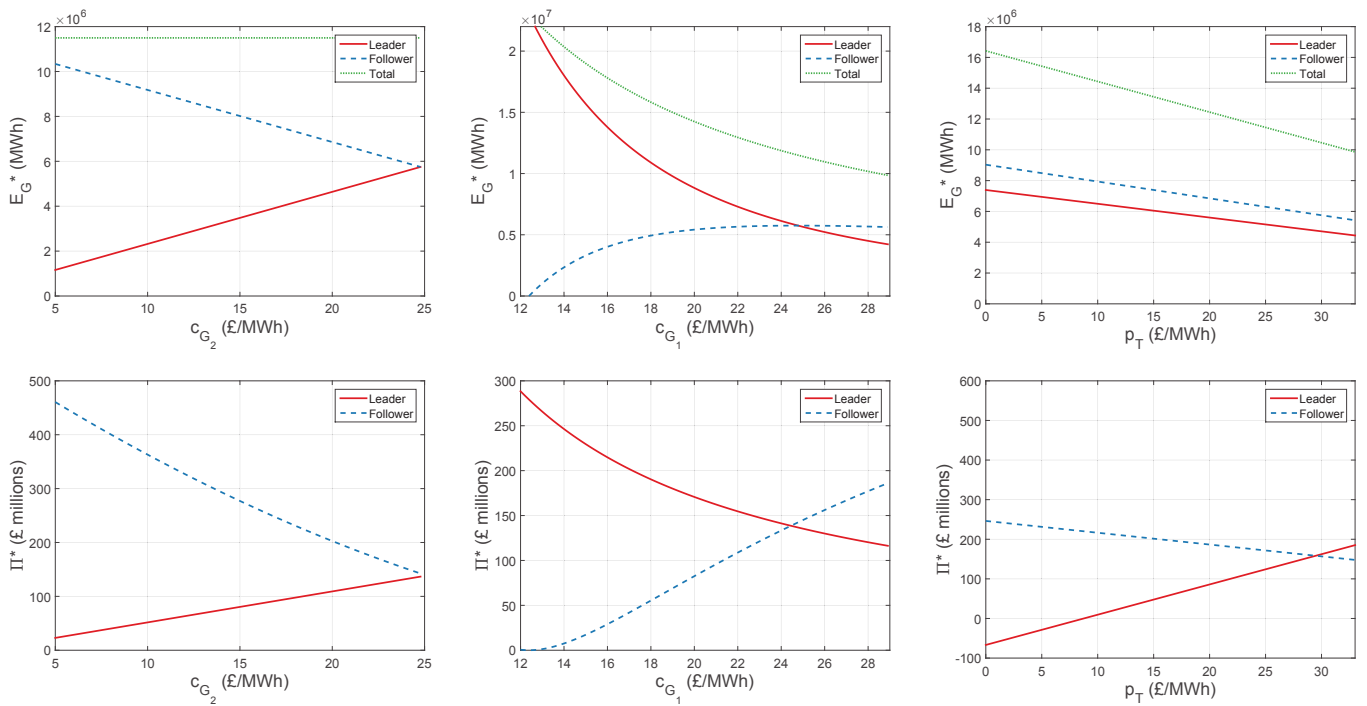
Fig. 4. Rows (1) and (2) show generation capacity built and profits at Stackelberg equilibrium, respectively, column (1) shows dependency on generation cost of local generators, (2) on generation cost of line investor and (3) on transmission fee

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