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# Game-theoretic modeling of curtailment rules and network investments with distributed generation ☆

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## HIGHLIGHTS

- Comparative study on curtailment rules and their effects on RES profitability.
- Proposal of novel fair curtailment rule which minimises generators' disruption.
- Modeling of private network upgrade as leader-follower (Stackelberg) game.
- New model incorporating stochastic generation and variable demand.
- New methodology for setting transmission charges in private network upgrade.

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## ABSTRACT

Renewable energy has achieved high penetration rates in many areas, leading to curtailment, especially if existing network infrastructure is insufficient and energy generated cannot be exported. In this context, Distribution Network Operators (DNOs) face a significant knowledge gap about how to implement curtailment rules that achieve desired operational objectives, but at the same time minimise disruption and economic losses for renewable generators. In this work, we study the properties of several curtailment rules widely used in UK renewable energy projects, and their effect on the viability of renewable generation investment. Moreover, we propose a new curtailment rule which guarantees fair allocation of curtailment amongst all generators with minimal disruption. Another key knowledge gap faced by DNOs is how to incentivise private network upgrades, especially in settings where several generators can use the same line against the payment of a transmission fee. In this work, we provide a solution to this problem by using tools from algorithmic game theory. Specifically, this setting can be modelled as a Stackelberg game between the private transmission line investor and local renewable generators, who are required to pay a transmission fee to access the line. We provide a method for computing the equilibrium of this game, using a model that captures the stochastic nature of renewable energy generation and demand. Finally, we use the practical setting of a grid reinforcement project from the UK and a large dataset of wind speed measurements and demand to validate our model. We show that charging a transmission fee as a proportion of the feed-in tariff price between 15% and 75% would allow both investors to implement their projects and achieve desirable distribution of the profit. Overall, our results show how using game-theoretic tools can help network operators to bridge the knowledge gap about setting the optimal curtailment rule and determining transmission charges for private network infrastructure.


## 1. Introduction

Renewable energy is crucial for achieving our decarbonisation goals and mitigating climate change. The Paris Agreement charts a new course of international effort to combat climate change with 195 countries agreeing to keep average global temperature rise well below 2 °C above pre-industrial levels and 129 countries ratifying so far. Driven by national and global initiatives, financial incentives and technological advances have permitted large

☆ This paper builds on significant extensions, both in theoretical results and new datasets, of preliminary work presented at two international conferences: AAMAS 2016 [1] and IEEE ISGT Europe 2016 [2].

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volumes of renewable energy sources (RES) to be connected to the electricity grid. In 2015, 147 GW of new renewable generation capacity was added globally, including 50 GW of new solar PV and 63 GW of wind power capacity, with total investment reaching an estimate of $285.9 billion [3]. The levelised cost of energy (LCOE) for several RES technologies, such as onshore wind or large scale PV, is currently competitive with conventional generation [4]. Renewable generation can provide benefits to network operators and consumers, but when installed with high penetration level, it might have negative effects on the operation, resilience and safety of the electricity grid. RES are intermittent and have variable power outputs due to constantly changing primary resources and weather patterns, which are difficult to predict. The challenges faced by network operators relate to reverse power flows, increased power losses, harmonics, voltage fluctuations, thermal capacity of equipment, frequency and voltage regulation and can compromise the system reliability [5].

An additional barrier is that grid infrastructure is inadequate to support continuous RES development or distributed generation (DG), especially in the area of distribution networks. Often high investment takes place in remote areas of the grid, where projects face favourable resource conditions and planning approval. Typically, in the UK, such areas are windy islands or peninsulas with limited or saturated connection to the main grid, facing network constraints, such as voltage, frequency or fault level violations in the absence of a network upgrade. Examples include the Shetland and Orkney archipelagos and the Kintyre peninsula, used as a case study to validate the model developed in this work.

As RES penetration increases, electricity grids require flexible services, which ensure safe operation and power system stability, such as forecasting techniques for RES output prediction, demand response, energy storage and generation curtailment. Most measures can be expensive, such as storage, technically challenging, or not yet mature enough for commercialisation. Hence, in light of the aforementioned barriers, the network places heavy dependence on curtailment at the present time.

Generation curtailment occurs when the excess energy that could have been produced by RES generators is wasted, as it cannot be absorbed by the power system and it cannot be transported elsewhere. In several countries including the UK, generators are compensated for lost revenues, but this results in higher system operation costs which are eventually passed on to end-consumer electricity prices. As more RES continue to be deployed, this practice cannot be sustainable and cost-effective, therefore smart solutions are required for further RES integration.

The two main techniques explored by network operators are Dynamic Line Rating (DLR) and Active Network Management (ANM). DLR uses rating technology and instrumentation to monitor the thermal state of the lines in real time and may improve the estimated capacity between 30% and 100% [6,7]. ANM is the automatic control of the power system by means of control devices and measurements that allow real time operation and optimal power flows. DLR and ANM can be combined to provide greater benefits in terms of curtailment reduction [8].

From the DNO perspective, both techniques imply controlling DG power outputs, hence innovative commercial agreements between generators and the system operator are required. Generators are offered interruptible, 'non-firm' connections to the grid, along with a set of rules about the order they are dispatched or curtailed, as opposed to traditional 'firm' connections, a solution preferred in many occasions to avoid high costs or enduring a long wait before getting connected [9]. These terms and conditions are known as 'Principles of Access' (PoA) and are the focus of this work. Such schemes have been supported by the UK Government through funding mechanisms encouraging DNOs to facilitate renewable connections [10].

The PoA options chosen by DNOs follow different approaches and each rule has both advantages and disadvantages in achieving desired objectives, such as cost-effectiveness, economic efficiency and social optimality [8]. A review on different rules is provided in Section 3 and related research works and discussion in Section 2. DNOs face the knowledge gap of implementing those curtailment rules that achieve greater benefits for all parties involved (RES generators and system operator). However, few works focus on the impact of different rules on the profitability of RES generators, crucially also affecting the investors' decision-making on future generation expansion. Our work studies the effects of different rules on the viability of RES developments. In particular, we provide results based on simulation analysis that show how several rules can decrease the capacity factor (CF) of different wind generators and how correlated wind speed resources affect the resulting curtailment.

The main rules found in the literature or applied in practical settings follow either a Last-in-first-out (LIFO) or a Pro Rata approach. LIFO is easily implemented and does not affect existing generators, but might discourage further RES investment. On the other hand, Pro Rata shares curtailment and revenue losses equally amongst all generators, who face frequent disruption every time curtailment is required. Note here that the fairness property plays a key role in maximising the renewable generation capacity built [1] and can lead to higher network utilisation [11]. Inspired by simultaneously satisfying objectives such as fairness, not discouraging future RES development and minimising disruption, we propose a new 'fair' rule which reduces the curtailment events per generator and guarantees approximately equal share of curtailment to generators of unequal rated capacity.

While smart solutions can defer network investment, the implications of curtailment extend to inefficient energy management and renewable utilisation, potential economic losses for RES generators, wasted energy and increased operation and balancing costs. Future adoption of electric vehicles (EVs) [12–14] and battery energy storage systems could be used to store excess RES generation and reduce curtailment. A long term sustainable solution to facilitate low-carbon technologies is network upgrade, such as reinforcing or building new transmission/distribution infrastructure. Grid expansion is a capital intensive investment, traditionally performed by system operators and heavily subsidised or supported by public funds. According to [15], the USA grid capacity investment would require an estimated $100 billion per year, between 2010 and 2030, with a minimum of $60 billion related only to the integration of RES. In the UK, an estimated £34 billion of investment in electricity networks could be required from 2014 to 2020, to accommodate new onshore and offshore projects [16]. Deregulated electricity markets and RES integration enable private investors participation in network investments. This market behaviour can be desirable from a public policy standpoint but it raises the question for system operators of defining the framework within which these private lines are incentivised, built and accessed by competing generators. Currently, DG investors bear a part of the costs required for their integration. In general the connection costs may vary, but usually include the full cost for the grid capacity installed for own use and a proportion of the costs for shared capacity with other customers, in the case of a network upgrade [17]. The remaining costs are recovered by the system charges borne by all grid users, representing approximately 18% of the average electricity bill of a typical UK household [18].

Moreover, current practices may lead to inefficient solutions in real-world settings, such as the problem of reinforcing transmission/distribution lines in outlying regions of Scotland, such as in the Kintyre peninsula, an area that has attracted major RES investment and is used as a case study in this paper. The scheme