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Opportunities for reducing curtailment of wind energy in the future electricity systems: insights from modelling analysis of Great Britain

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Abstract

This paper assesses how operational flexibility and the curtailment of renewable energy are connected using a unit commitment and economic dispatch model that includes operational characteristics of conventional power plants and system constraints. A Great Britain test system is analysed under different scenarios of wind (onshore and offshore) and solar installed capacity, showing that an increase in curtailment is mostly expected as wind deployment increases. This curtailment reaches 17% of the annual available variable renewable electricity generation at high wind and solar installed capacities and is mainly driven by the inertial requirement. The best approach to reducing curtailment is, therefore, to reduce the inertia floor by relaxing Rate of Change of Frequency limits. For the assumed curtailment costs, onshore wind presents a stronger correlation with overall curtailment than offshore wind and solar, albeit influenced by the levels of solar installed capacity. Significant reductions in curtailment can be achieved if wind contributes to system balancing requirements. This emphasizes the importance of ensuring that variable renewables are technically able to contribute to system balancing, wherever feasible, and of improving access to revenue streams that incentivise flexible operation of variable renewable generation.

Keywords: curtailment; flexibility; wind; solar; inertia; reserve.

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Symbol	Description	Typical units
$\boldsymbol{\mu_t^{up}}$	Largest credible loss in generation	GW
$\boldsymbol{\mu_t^{dn}}$	Largest credible loss in demand	GW
$\boldsymbol{R_t^{up,sp}}$	Upward spinning reserve	GW
$\boldsymbol{R_t^{dn,sp}}$	Downward spinning reserve	GW
$\boldsymbol{R_t^{up,st}}$	Upward standing reserve	GW
$\boldsymbol{R_t^{up,st}}$	Downward standing reserve	GW
$\boldsymbol{\sigma_t^D}$	Demand uncertainty	GW
$\boldsymbol{\sigma_t^W}$	Wind generation uncertainty	GW
$\boldsymbol{\sigma_t^S}$	Solar generation uncertainty	GW
$\boldsymbol{W_{sys}}$	System inertia	GVA.s
$\boldsymbol{W_{sync}}$	Inertial contributions from synchronous generators	GVA.s
$\boldsymbol{W_{load}}$	Inertial contributions from demand	GVA.s
$\boldsymbol{S_{sync}}$	Rated power of each synchronous generator	GVA
$\boldsymbol{H_{sync}}$	Inertia constant	s
$\boldsymbol{W_t^c}$	Curtailed wind	GW
$\boldsymbol{W_t}$	Wind generation	GW
$\boldsymbol{S_t}$	Solar generation	GW
$\boldsymbol{L_{min}}$	Minimum level of conventional generation	GW
$\boldsymbol{D_t}$	Total demand	GW
$\boldsymbol{D_{net,t}}$	Net demand	GW
$\boldsymbol{VRE_t}$	Variable renewable generation	GW
$\boldsymbol{VRE_t^{c,inertia}}$	Variable renewable generation curtailed	GW
$\boldsymbol{P_{i,min}}$	Minimum export limits	GW
$\boldsymbol{P_{i,max}}$	Maximum export limits	GW

Table. 1. Nomenclature used throughout the paper.

1. Introduction

Recent years have seen several countries making increasingly substantial use of variable renewable electricity generation (VRE). It is also expected that the contribution of these sources to electricity generation will continue to grow in many countries in the coming decades [1]. This trend is likely to have a significant effect on power system design and operation, since VRE is currently typically non-dispatchable[2]. Because of this, the *net demand, i.e. the difference between total demand and VRE generation,* to be served by conventional power plants becomes more variable and uncertain than the gross demand. This imposes additional system balancing challenges to be mitigated by the system operator (SO) [2]. Moreover, the non-synchronous connection of typical VRE reduces the system inertia, hindering the stabilization of the system frequency in contingency events [3].

This brings forth the need for additional flexibility in other aspects of the power system. System flexibility can be defined as the ability of the power system to accommodate variability and uncertainty from electricity generation and demand while maintaining statutory reliability requirements [4]. This variability is addressed via *balancing services* that include (i) *reserve services* where capacity is able to respond to unpredicted deviations in generation or demand and (ii) *regulation (e.g. frequency response)* where the continuous flow of supply and demand of power is matched on a second-by-second basis [5].

In many power systems, thermal generators have traditionally been the system backbone and the main source of flexibility. The availability of these generators to provide the necessary balancing services reduces as VRE displaces conventional generation. Without other sources of flexibility apt to provide these services, VRE curtailment is typically required to ensure there is sufficient thermal generation to provide them.

This curtailment of VRE imposes limits on the achievement of climate change targets and may hamper investment in new projects [3]. Payments associated with curtailment also increase system balancing costs which are ultimately passed to consumers through their energy bills. It is therefore important to quantify the future levels of curtailment likely to occur in power systems and fully explore options that could allow curtailment reduction.

One important contributor to curtailment is maintaining the inertial level in the power system, so that the stability of system frequency is guaranteed [3]. The *inertial constraint* implied by the need to maintain a sufficient inertial level varies between different power systems and is linked to the allowable RoCoF (Rate of Change of Frequency) in fault conditions. The decline of the system inertia is considered one of the main challenges for SOs, particularly in synchronously isolated systems (e.g. Ireland, Great Britain [6]) where it is likely to induce an increase in curtailment.

In this paper the British (GB) power system was chosen as a case study to appraise curtailment driven by balancing requirements and the inertial constraint as additional VRE capacity is installed. In particular, this work tests the hypothesis that the most effective approach to reducing VRE curtailment is to make plausible changes to inertia constraints. The potential for reducing curtailment by allowing wind to contribute to system balancing services as a complementary approach to reducing VRE curtailment is also assessed.

This paper uses a system-wide dynamic programming unit commitment and economic dispatch (UCED) model to explore the potential value of wind contribution to power system flexibility and its effect on curtailment for a GB case study. In particular, it addresses four main objectives:

- provide a baseline of plausible future levels of curtailment in GB due to balancing requirements with varying levels of wind and solar deployment;
- analyse the impact of this curtailment on VRE contribution to electricity generation and CO_2 emissions;

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[2] Currently this power can neither be cheaply accumulated nor prearranged for production because of high cost of storage technologies and volatile nature of weather.

- evaluate the effect of the reduction of the currently imposed inertia floor on wind and solar curtailment; and
- appraise the impact of wind contribution to the balancing services as a measure to mitigate curtailment.

Although other strategies exist to mitigate balancing-related curtailment [7], the primary focus of this work is on the value of wind contribution to power system flexibility and its effect on curtailment. The remainder of this paper is structured as follows. A literature review in Section 2 provides an introduction to other relevant studies in this field and locates this work in the wider literature context. Section 3 describes the methods used including the model description, the assumptions and the characterisation of the scenarios. Section 4 presents and discusses the obtained results followed by a conclusion in Section 5 that highlights the most important findings.

2. Literature Review

Studies with a specific focus on curtailment have been gaining attention over the last years in countries with high penetration of wind or solar, e.g. Germany, the US and Ireland [7]. These studies are part of a wider research field focusing on VRE integration, which emphasize the need for additional system flexibility to cope with the increased variability and uncertainty introduced by VRE [8]. The majority of these studies however, oversimplify (or disregard) the operational characteristics of thermal generators or potentially significant aspects of system requirements.

In their work, Brouwer et al. [9] review 19 wind integration studies, some including solar PV generation, and report that wind curtailments are mainly driven by network constraints. The study concludes with a recommendation to use UCED models to evaluate the power system impacts of VRE.

From a European perspective, Gils et al. [10] developed an energy system model, REMix, and applied it to several wind-solar scenarios. They underline the importance of storage and flexibility technologies in high VRE penetration scenarios. While they consider a broad mix of technologies, the constraints of the thermal generators and operational requirements of the system are not modelled. The percentages obtained for the likely future curtailment arise from a combined perspective of interconnected power systems. Although this is an effective approach to provide a wide view of VRE integration challenges for policy planning, it neglects the particular characteristics of the generating mix and power systems requirements in the different countries.

Almenta et al. [11] use a UCED model built in PLEXOS to analyse the future wind curtailment and constraint in Northern Ireland. The model evaluates the wind constrained due to limits in the local networks. The model also considers the system balancing requirements and day-ahead demand and wind uncertainties for the calculation of reserves. The findings showed significant reductions in curtailment when the system non-synchronous penetration (SNSP) limit increases. Mc Garrigle et al. [12] model the electricity system in the island of Ireland and estimate the levels of curtailment in 2020. The model takes into account operational constraints from conventional generators considering different levels of offshore wind and SNSP limits. The results also show a significant reduction in curtailment when the SNSP limit increases.

For the case of GB's power system, Pfenninger & Keirstead [13] use a high space-time resolution model to evaluate the impact of increasing penetration of VRE generation. Calculating the levelised cost of electricity, they evaluate a wide range of scenarios and conclude that shares above 80% of VRE are feasible albeit with additional technologies and interconnection to provide flexibility. However, the model does not consider operational constraints from thermal generators or from the power system.

A recent study from Raugei et al. [14] used a unit commitment model to assess the performance of the UK power system with high solar PV installed capacity. They report annual wind curtailment ranging from 14% to 22%. While the model integrates the constraints of thermal generators and includes a detailed treatment of reserve services, it does not consider the inertial requirements. The reduction of the system inertia and its effect on the frequency stability has been identified as one of the main challenges in future power systems [15]. Teng and Strbac investigate this in the context of the future GB system, introducing a novel methodology that demonstrates potential benefits of wind contribution to primary frequency response and inertia [16].

Additionally, Joos & Staffell [17] investigate the integration costs of VRE in Britain and Germany, focusing on congestion and balancing costs. They review curtailment practices and evaluate the contribution of VRE to balancing costs, including the potential benefits from a contribution of wind to balancing services. They conclude that additional VRE can be accommodated without increasing costs solely by improving system operation, for which they propose several policy strategies that enable VRE to provide balancing services and improve system operation (e.g. shorter product lengths and substitution of tenders for frequent auctions).

A similar conclusion was obtained by Strbac et al. [18] in a report that analyses the integration costs of low-carbon technologies. This study demonstrates the importance of increasing system flexibility to achieve a cost-effective decarbonisation of the GB electricity system, for which market mechanisms that reward flexibility are deemed critical. The study assumes that the frequency requirements for inertia will change in the future, thus the current inertia floor is not considered.

More recent research studies are also focusing on other technologies to provide flexibility. Gupta et al. [19] evaluate optimization strategies for hydropower stations to maximise generation in a power system with high wind and solar penetration, alongside contributing to system balancing. McPherson and Tahseen [20] evaluate the potential of storage in electricity systems with increasing VRE capacity. The utility of storage is found to be dependent on VRE penetration and system flexibility – only effectively mitigating curtailment when the conventional generation in the system is sufficiently flexible. Taibi et al. [21] utilise PLEXOS to evaluate the impact that vehicle-to-grid and the provision of ancillary services would have in production costs, finding that smart charging techniques would reduce curtailment and facilitate VRE integration. From the demand perspective, load shifting and demand-side management have also gained attention. Hungerford et al. [8] study the potential of hot water system control regimes in Australia and find that optimised control could reduce VRE curtailment and facilitate its integration, showcasing the value of load flexibility in an energy system with high renewable penetration.

This study aims to contribute to the developing insights on the most important factors that trigger VRE curtailment. It focuses particularly on determining which approaches are likely to make the most significant contribution to reducing VRE curtailment in future systems. It demonstrates the use of a UCED model that takes into account the requirements from conventional generators and system balancing using a GB case study.

The novelty of this work lies in the combination of wind and solar generation in a modelling framework that effectively integrates constraints from thermal units and the balancing requirements of the power system, focusing on the effect of the inertial constraint and on the potential contribution of wind to the balancing services. This study also analyses curtailment changes with respect to different and mixed VRE deployment and reports the rate of change of curtailment and CO_2 emissions with increasing VRE penetration. This latter analysis is important for understanding the marginal contribution of additional VRE capacity thus allowing policy-makers and investors to determine whether additional VRE deployment is likely to make an effective contribution to the power system.

3. Methods and Assumptions

The unit commitment and economic dispatch (UCED) model [22] simulates the performance of the future GB power system with hourly wind and solar generation data. It optimises the short-term scheduling of conventional generators (that can span from a week to a year) with a time resolution of an hour considering such constraints as the system balancing requirements and generator operational constraints.

The model was developed in the MatLab programming and modelling environment at the Institute for Energy Systems in the School of Engineering at the University of Edinburgh [23]. It uses a priority-list Dynamic Programming (DP) solution technique that utilises the prior evaluation of the feasible states of meeting demand and reserve constraints to overcome the *curse of dimensionality* and the high computational-time requirement typical of the DP technique.

The objective function of the unit-commitment block is to minimise the overall system costs given the stipulated constraints. This block uses demand, wind and solar time series (Section 3.1) to ensure the committed units are able to meet the net demand under the system requirements (Section 3.2) and generators' operational constraints (power output constraints with minimum and maximum export limits, ramping capability and minimum up and down times for every unit). The economic-dispatch block thereupon adjusts the generation levels to balance the net demand with the least cost. Lastly, the model provides a range of outputs for every time-step, e.g. curtailment values, power output of every unit, available reserves and CO_2 emissions (i.e. from conventional generators, CCS captured emissions, emissions during operation and at start-up and shut-down events, according to the plant characteristics in the supplementary material).

The model assumes a single-bus transmission network to avoid unnecessary complicated modelling of the transmission system constraints. Although transmission network constraints can be an important consideration in power systems and may contribute to the curtailment, this type of curtailment is decreasing in GB and it is expected to be further reduced through ongoing grid reinforcement and interconnections [24].

3.1. *Input data*

A high resolution wind generation dataset is obtained from [23] for the years 2002–2010. These data are derived from the extensively validated wind-speed dataset developed by [25] which is believed to provide a credible representation of the future wind deployment in GB. The dataset simulates the hourly power output of existing and future onshore and offshore windfarms in the entire UK capturing the effect of spatial distribution.

Solar PV generation is simulated for 2002–2014 from a recently developed dataset of hourly capacity factors for the UK by Pfenninger and Staffell [26]. Solar capacity factors for Europe are modelled using the NASA MERRA and MERRA-2 meteorological reanalyses, and Meteosat-based SARAH satellite datasets. For this work, these different datasets were compared with annual average capacity factors calculated with half-hourly PV generation data from [27] and cumulative installed capacity provided by [28]. As a result, the MERRA-2 dataset was found to give the best approximation of the calculated average capacity factors and was therefore deemed the most suitable. Hourly PV generation is then modelled with these capacity factors assuming several scenarios of installed capacity. This hourly generation intends to represent the electricity coming from the combination of small (<5 MW and mainly rooftop) and large-scale solar. It is acknowledged that large solar installations would yield slightly higher efficiency than rooftop panels, yet this difference is not considered significant for this study.

Hourly time-series of weather-corrected electricity demand for 2002–2010 are obtained from historical datasets of the GB system operator, National Grid (NGESO) [23]. The same year, 2010, is used for the demand and renewable generation datasets to enable the simulation of real demand patterns and load variability, temporally matched with wind and solar generation. It is not fully understood how the future change in the demand patterns with an increased electrification, efficiency improvements and consumption awareness from consumers will affect the levels of demand, the profile shape and the forecasting accuracy; hence they are not considered in this study.

The conventional generation portfolio used is shown in Table 1. The costs and technical parameters of the thermal units are available in the supplementary material.

Units	**Number**	**Cumulative capacity (GW)**
Nuclear	8	13.2
Combined-cycle Gas Turbines (CCGT)	40	36
CCGT + PCC (Post-combustion Carbon Capture)	4	3.6

Open-cycle Gas Turbines (OCGT)	20	11.3

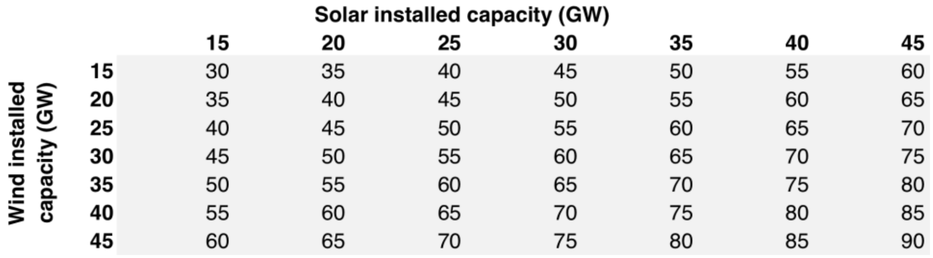
Table 1. Conventional generation portfolio.

The natural gas prices – obtained from the Department for Business Energy and Industrial Strategy (BEIS) [29] – and CO_2 prices assumed are shown in Table 2. Sensitivity analyses undertaken to appraise the effects of variations in the natural gas and CO_2 price assumptions showed that changes in these prices have a negligible impact on the results obtained from this study (see supplementary material).

	Price
Natural gas	70p/therm
CO_2 prices	£25/tCO_2

Table 2. Natural gas and CO_2 prices assumed.

A matrix of scenarios is used to explore future levels of curtailment in GB across a plausible range of VRE installed capacity. These scenarios are composed of 49 possible combinations of installed wind and solar capacity from 15 to 45 GW in 5 GW increments, which are deemed large enough to produce a significant quantifiable change in final curtailment values. This is represented in Table 3, where the shaded area contains the total installed VRE capacity resulting from the combination of wind and solar capacity.

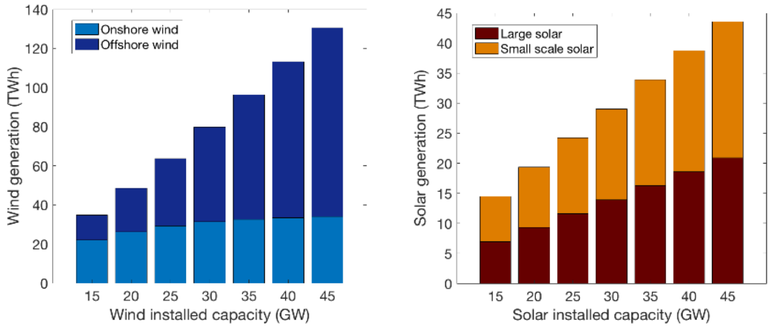


		Solar installed capacity (GW)						
		15	**20**	**25**	**30**	**35**	**40**	**45**
Wind installed capacity (GW)	**15**	30	35	40	45	50	55	60
	20	35	40	45	50	55	60	65
	25	40	45	50	55	60	65	70
	30	45	50	55	60	65	70	75
	35	50	55	60	65	70	75	80
	40	55	60	65	70	75	80	85
	45	60	65	70	75	80	85	90

Table 3. Matrix of scenarios of VRE installed capacity (GW).

Each scenario is simulated for 365 days with a granularity level of an hour for 2010 weather and demand. The lower boundary represents an installed capacity of wind and solar generation close to the actual (2019) levels, and the upper boundary of 45 GW for both wind and solar is consistent with previous studies in this field [14] and several scenarios developed by NGESO for 2030 and 2050, respectively [30].

Fig. 1 (a) represents the wind generation at every installed capacity as calculated by Bruce et al. [23] and used in this study. As overall wind capacity installed increases, onshore wind remains nearly stagnant while offshore wind increases significantly, representing the high potential of this resource in GB [31]. Fig. 1 (b) illustrates the solar generation obtained from the hourly capacity factors previously introduced and multiplied by the estimated installed capacity. The distribution of small- and large-scale solar has been assumed to remain constant throughout the scenarios and equal to the current distribution of 52% small-scale solar and 48% large-scale solar [28]. Despite NGESO predictions of future capacity dominated by industrial or large PV, this is considered a reasonable simplification, since the installation trend to date has been similar in both small- and large-scale solar. Moreover, the future evolution of large-scale solar is highly uncertain, partly due to the recent changes in the incentives for this technology available in GB.



(a) (b)

Fig. 1. Wind and solar generation with installed capacity across scenarios.

3.2. System constraints

The integration of VRE in the power system imposes additional variability and uncertainty that will require corresponding electricity system constraints to be modified. Additional reserves are needed to account for VRE uncertainty, and a minimum inertia floor is necessary to guarantee the stability of the system in a contingency event, given the increase of non-synchronous sources [5].

3.2.1. Reserves

Upward and downward reserves are modelled following a deterministic criterion for the largest credible loss in generation (μ_t^{up}) and demand (μ_t^{dn}), and a dynamic criterion to account for imbalances due to demand, wind and solar forecast errors 4 hours ahead of real-time. These reserves are held in spinning (provided by part-loaded generators) and standing reserves (provided by offline generators) as shown in equations (1) and (2). They are scheduled to cover imbalances in 99.95% of the events, which corresponds to 3.5 standard deviations (σ) in a normally distributed function, in compliance with the current GB reliability standard [4].

$$R_t^{up} = R_t^{up,sp} + R_t^{up,st} = \mu_t^{up} + 3.5\sqrt{(\sigma_t^D)^2 + (\sigma_t^W)^2 + (\sigma_t^S)^2} \quad (1)$$

$$R_t^{dn} = R_t^{dn,sp} + R_t^{dn,st} = \mu_t^{dn} + 3.5\sqrt{(\sigma_t^D)^2 + (\sigma_t^W)^2 + (\sigma_t^S)^2} \quad (2)$$

Demand, wind and solar forecast uncertainties are represented as normally distributed functions with a zero mean. Demand uncertainty is modelled with a standard deviation(σ_t^D) of 1% of predicted demand. Wind uncertainty is represented with a standard deviation (σ_t^W) of 10% of the wind generation. This considers the forecast accuracy target adopted by NGESO [30] and the higher prediction errors characteristic of offshore wind [33].

A standard deviation (σ_t^S) of 8% of the solar generation is approximated from [33], given the lack of data regarding PV forecasting errors in the UK. This accounts for the variability of solar generation due to the effect of clouds, as the variation introduced by the sun path is assumed to be fully predictable and thus integrable in the conventional plant scheduling by the SO.

For simplicity, this paper assumes a normal distribution for the solar forecast-errors and also that demand-wind-solar uncertainty can be assumed to be uncorrelated so that they can be combined into a single equation. Further work could consider other distributions for solar uncertainty [34] and also other approaches to characterising the combined behaviour of demand-wind-solar [35].

Curtailed wind W_t^c is allowed to reduce the upward reserve requirement — a practice already followed by PSCO in Colorado [7]. The possibility to reduce the reserve requirement when the scheduled wind production is lower than σ_t^W is included in accordance with previous studies, avoiding a possible overestimation of this service [21,31]. Equation (1) thus becomes (3) by taking the smallest figure between σ_t^W and the scheduled wind generation:

$$R_t^{up} = \mu_t^{up} + 3.5\sqrt{(\sigma_t^D)^2 + min(\sigma_t^W, W_t - W_t^c)^2 + (\sigma_t^S)^2} \quad (3)$$

Wind contribution to downward reserve has been evaluated in previous studies [17] and is currently under consideration by NG for GB, since it has become an economic service in periods of high wind and low demand [36]. Its contribution is formulated from equation (2), assuming that unexpected increases in generation due to wind forecast uncertainty can be counteracted with small wind curtailments:

$$R_t^{dn} = \mu_t^{dn} + 3.5\sqrt{(\sigma_t^D)^2 + (\sigma_t^S)^2} \quad (4)$$

The value of wind contribution to this service is investigated in a case study (Section 4.5). The ability of solar PV to provide reserve has been seldom studied in the literature, and there is no previous practice or demonstration; therefore, solar contribution to this balancing service is not considered in this work.

3.2.2. Frequency response and inertia

Inertia is defined as the stored kinetic energy in a rotational mass and plays an essential role in limiting the *rate of change of frequency* (RoCoF). The inertia of the system is thus a fundamental property for managing the short-term frequency instability providing dynamic and immediate response to frequency deviations [6]. The system inertia W_{sys} corresponds to the sum of the inertial contributions from the synchronous generators connected to the system W_{sync} and the load W_{load} [37]:

$$W_{sys} = W_{sync} + W_{load} \quad (5)$$

$$W_{sync} = H_{sync} \cdot S_{sync} = \sum_{i=1}^{N} (H_i \cdot S_i) \quad (6)$$

where S_{sync} is the rated power of each synchronous generator (GVA) and H_i its inertia constant (s), defined as the time the machine can supply its rated power exclusively from its stored kinetic energy.

The system inertia has to be maintained over a certain limit to avoid a cascade tripping effect from embedded generators if a frequency disturbance occurs, effectively imposing an inertia floor. This stems from the islanding protections of most distributed generators, set to trip when a certain RoCoF threshold is exceeded [15]. Whilst the RoCoF limit has been recently modified in the GB Distribution Code, some protection relays are still set to the previous threshold of 0.125 Hz/s [5]. For the initial scenarios, a minimum level of conventional generation is thus imposed to maintain the inertia level, which is set to 130 GVA.s in compliance with the post-fault inertia floor currently established by NGESO [5].

An inertia constant H_{sync} of 6 s is assumed in accordance with the values found by Ashton et al. [36] for the GB system. This is considered a reasonable approximation, since the inertia constant of the system varies depending on the contributions of the units synchronised at every moment, and future changes in the inertia constants of the generators are not well understood [37]. Large synchronous generators are assumed to provide 70% of the system inertia as reported by [5]. A minimum level of conventional generation L_{min} of 15 GW is then approximated from equation (7), derived from (6).

$$L_{min} = S_{sync} = W_{sync}/H_{sync} = 0.7 \cdot W_{sys}/H_{sync} \quad (7)$$

The GB Distribution Code has been modified to withstand RoCoFs within 0.5-1 Hz/s. It is thus expected that the inertia floor will drop in the future, following the adaptation of all distributed generation to the new limits. This is investigated further in Section 4.5.

While the focus of this paper is on the system inertia, the thermal units providing the minimum load are also assumed to contribute to dynamic frequency response services (i.e. primary, secondary and high frequency response). It is also envisaged that wind farms will be able to provide fast frequency response in GB, contributing to some part of the system inertia [16].

This contribution by wind is possible by combining the stored rotational energy with fast-response power electronics, which enables the emulation of an inertial response, i.e. *synthetic inertia*. For example, Ela et al. [39] provide a comprehensive study of options for active power control from wind power. They conclude that wind power plants can provide active power control, although careful engineering analysis to ensure optimal deployment is also recommended.

Volger-Finck and Früh [40] model the GB transmission system for a range of loads and wind penetrations. They demonstrate that introducing inertial control of wind turbines or dynamic frequency control support (with deployment times of around 1s) has the potential to significantly reduce requirements for conventional primary frequency response.. New fast-frequency products such as the *Future Frequency Response* products from *NGESO* could enable this contribution.

3.2.3. Curtailment

Curtailment is performed in two stages in the model as shown in Fig. 2. The first stage includes wind and solar curtailment to ensure the minimum load for the inertia floor is maintained:

$$D_{net,t} = D_t - VRE_t = D_t - (W_t + S_t\,) \quad (8)$$

$$VRE_t^{c,inertia} = max\,(0, L_{min,t} - D_{net,t}\,) \quad (9)$$

where $L_{min,t}$ is the minimum load, and $VRE_t^{c,inertia}$ quantifies the amount of renewable generation that has to be curtailed due to the inertial constraint (*inertial curtailment*) at every time-step N.

In the second stage, curtailment may occur to ensure there is a feasible combination of thermal generation to meet the net demand and required reserve, subject to the following constraints:

$$D_{net,t} - R_t^{dn,sp} \geq \sum_{i=1}^{N} P_{i,min} \quad (10)$$
$$D_{net,t} + R_t^{up,sp} \leq \sum_{i=1}^{N} P_{i,max} \quad (11)$$

where $P_{i,min}$ and $P_{i,max}$ are the minimum and maximum export limits of the thermal units N.

If there is no feasible combination of plants that can meet the above two constraints, wind and solar are sequentially curtailed in five rounds — three rounds of 1 GW and two rounds of 2 GW — until a feasible state is reached. This *sequential curtailment* guarantees that the conventional generators have sufficient head-room and foot-room to provide the upward and downward reserves required.

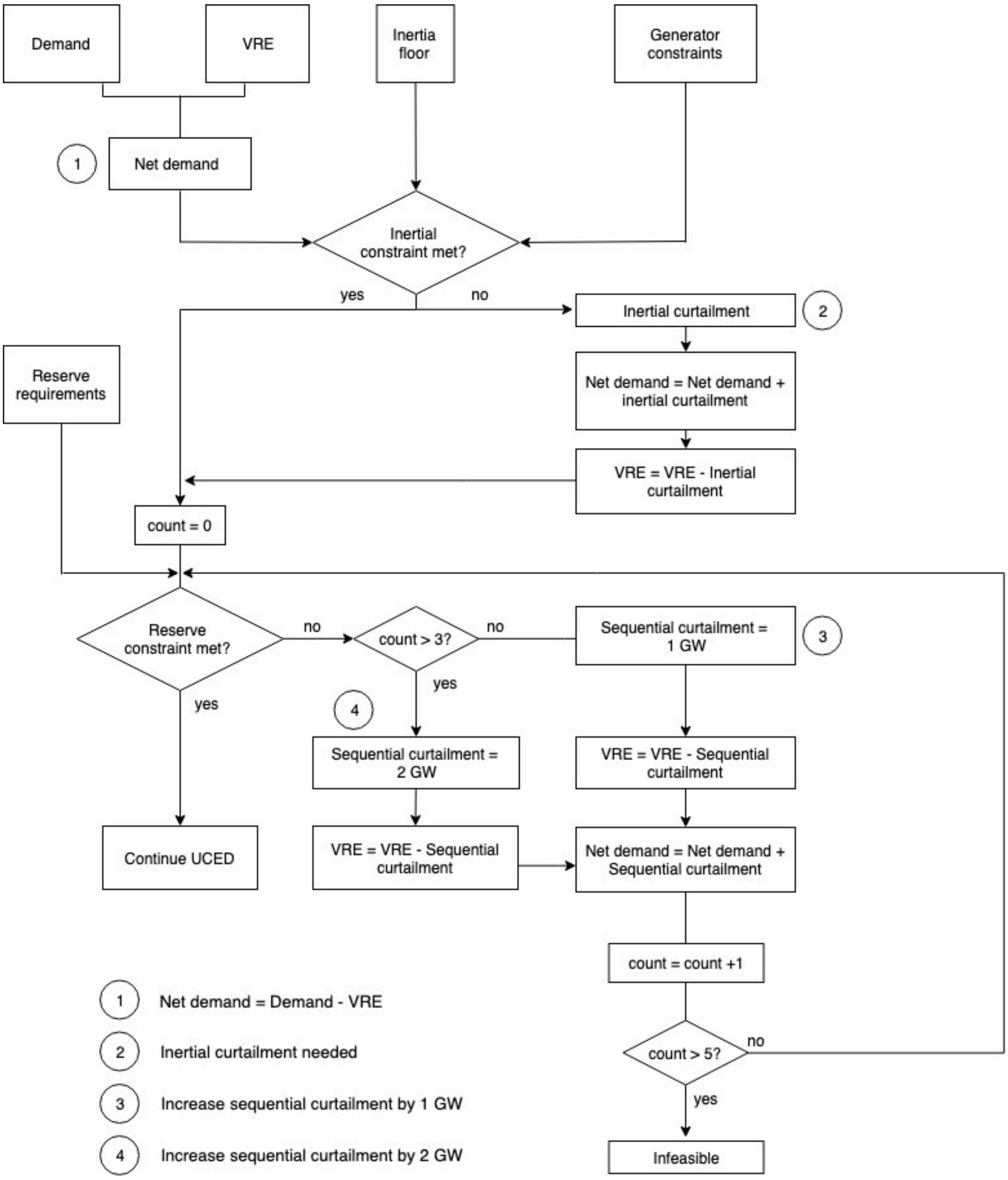


Fig. 2. Flow diagram of the curtailment process in the UCED model.

The order of curtailment is defined according to the constraint payments currently allocated in GB to each technology (Table 4), preserving the principle of the least-cost dispatch. This reflects the current higher strike price of onshore wind than large-scale solar within the UK Contract for Difference (CfD) scheme, albeit with reduced prices to reflect the recent changes in the regulation that cease future support for these technologies. Offshore wind's curtailment price is assumed in accordance with the future CfD support at the time that this work was undertaken [41].

	Technology order	**Curtailment price**
1.	**Large scale solar PV**	45 £/MWh
2.	**Onshore wind**	50 £/MWh
3.	**Offshore wind**	100 £/MWh
4.	**Small scale solar PV**	100 £/MWh

Table. 4. Curtailment order and prices.

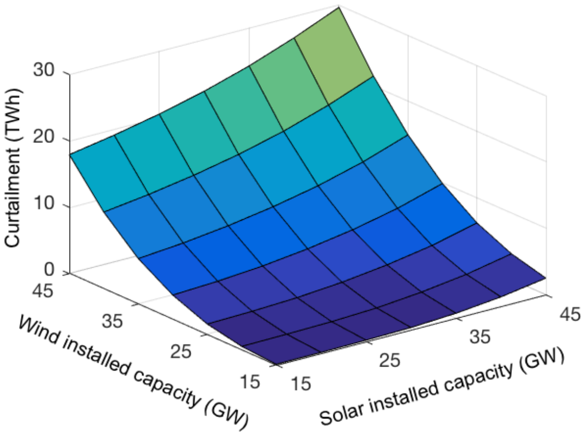
Small scale solar currently benefits from feed-in tariffs (FiTs) and acts directly to reduce the household demand curve. This is considered more challenging to be curtailed by the SO, and no previous experience has been found on roof-top solar curtailment in other countries either. Hence, it is placed last in the curtailment order with an assumed price of 100 £/MWh. It should be noted that most solar installed capacity and part of the onshore wind capacity[3] are connected to the distribution network [42]. Active Network Management[4] is expected at the distribution level to enable the SO or distributed SO (DSO) to control and curtail distributed generation as part of the Balancing Mechanism.

4. Results and discussion

The following section presents and discusses the results obtained from the modelling of the formerly described scenarios. First, Section 4.1 presents the levels of annual curtailment that result from increasing installed capacity of wind and solar. A correlation analysis to consider the relationship between the curtailment of different technologies and the total curtailment is then undertaken in Section 4.2. Sections 4.3 and 4.4 evaluate the effect that curtailment has on the capacity utilisation as additional wind and solar are installed, by analysing the penetration of VRE and CO_2 emissions at different installed capacity. Lastly, section 4.5 undertakes a case study analysis to showcase the effect of the inertial requirement on curtailment levels and understand the role that wind generation can play in system balancing, i.e. how the use of wind for synthetic inertia and downward reserve would affect VRE curtailment.

4.1. Total curtailment and its distribution per technology

The first and most straightforward indicator to assess the impact of increased wind and solar installed capacity on the levels of curtailment is the amount of curtailed energy throughout the year. The results are presented in Fig. 3 and additional data are available in summary tables in the supplementary material. Wind has a higher impact than solar on the levels of curtailment, reflected in the steeper slopes along the axis of the wind installed capacity. Curtailment levels reach a maximum of 29.6 TWh per year corresponding to 17% of the available VRE generation – 8.8% of the annual electricity demand. It is important to note that this curtailment is solely driven by the minimum load requirement for the inertia floor. No sequential curtailment is needed since this minimum load is high enough to guarantee all the required reserve services.



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[3] Offshore windfarms use transmission assets and are thus classified as part of the Transmission System even if connected onshore to the Distribution Network.

[4] Active Network Management enables the real-time control and monitoring of distributed generators by the distribution network operators.

Fig. 3. Curtailed energy (TWh) per year for different combinations of installed wind and solar capacity.

The amount of curtailment is illustrated in Fig. 4. The x-axis represents the scenarios of wind installed capacity and the columns inside each group correspond to the solar installed capacity. Onshore wind and large-scale solar are the technologies that experience the highest levels of curtailment. No small-scale solar curtailment occurs in any scenario. The maximum level of penetration achieved is 144.5 TWh, providing 43% of the annual demand. Without curtailment, this level would rise linearly reaching 174 TWh equivalent to 52% of the total demand. This has severe economic implications as the curtailment costs could add up to £1.8 billion in one year, considering the payments per MWh curtailed assumed in Section 3.2.3 [43]. These payments would increase the system balancing costs and eventually raise consumers' bills.

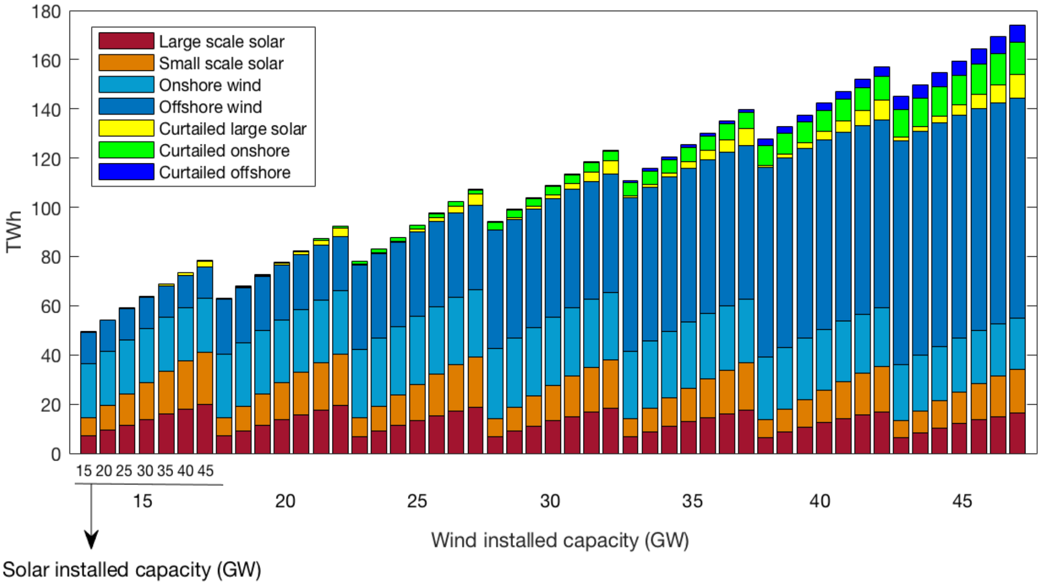


Fig. 4. Amount of VRE generated and curtailed (TWh) across all scenarios. The x-axis represents the scenarios of wind installed capacity and the columns inside each group correspond to the solar installed capacity.

4.2. Correlation analysis

The Pearson product-moment correlation is used to analyse the changing relationship between the curtailment of different technologies and the total curtailment, the results are presented in Fig. 5. The highest correlation is seen for onshore wind, achieving a coefficient of 0.985 at low solar penetrations and decreasing as solar installed capacity rises. At low solar deployment, the correlation coefficient drops at above 35 GW of wind installed capacity, as onshore wind therein remains constant while offshore wind increases. This is driven by an increase in offshore wind curtailment, reflected in its higher correlation coefficient at large wind installed capacity.

The solar correlation coefficient follows a similar pattern to onshore wind, albeit with lower values. Curtailment is negatively correlated with the net demand that is to be met by conventional generation, taking place at periods when the latter is low to maintain the minimum load. These periods are generally seen during the night when the lack of solar generation situates onshore wind as the first source of curtailment, which is consistent with the findings in Bird et al. [7] and Raugei et al. [14]. This makes wind more likely to be curtailed, despite being placed after solar in the curtailment ranking order, which explains the lower correlation coefficient of solar. Nevertheless, it is important to note that as solar capacity rises, so does its correlation with curtailment. This stems from the 'duck curve' produced at midday by solar generation: a dip in the net demand similar to the one occurring overnight. This effect of high solar penetration has been reported in previous studies in the US [44].

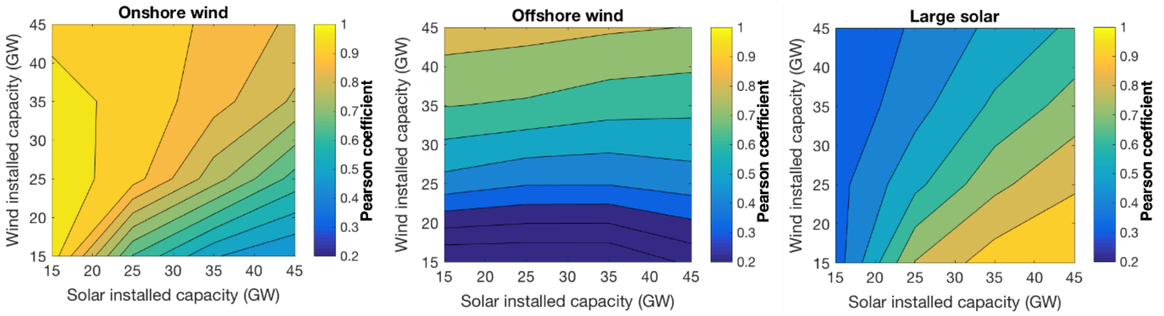
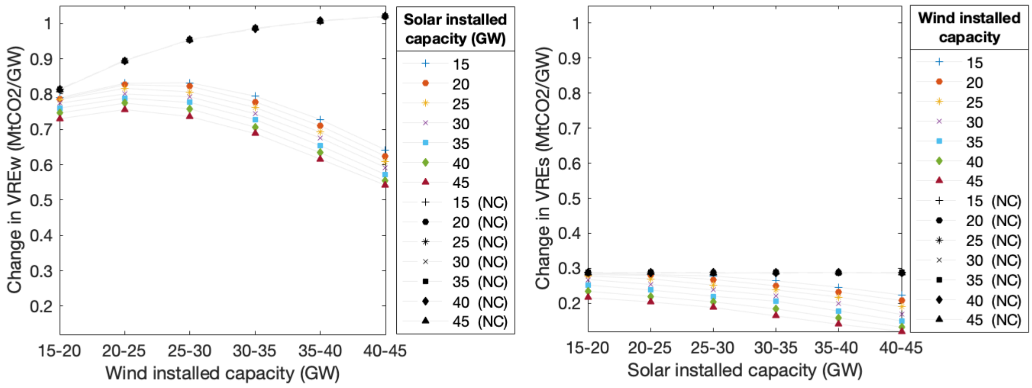


Fig. 5. Pearson correlation coefficient between the amount of curtailment of each technology and the total curtailment.

4.3. Variable renewable energy penetration

Although the penetration of wind and solar generation increases as additional capacity is installed, this increase is truncated by curtailment. To analyse in more detail how curtailment processes affect the capacity utilisation, the rate of change in the combined penetration of wind and solar for additional capacity instalment is calculated, as shown in Fig. 6. This relation is obtained by approximating the partial derivatives of the VRE penetration, the percentage of demand met by wind and solar, with respect to the installed capacity of each technology. More detail on the calculations can be found in the supplementary material.



(a) (b)

Fig. 6. Rate of change of VRE penetration in percentage points (PP) with every additional GW of (a) wind and (b) solar installed capacity (GW) considering curtailment and not considering curtailment (NC)

Fig. 6 (a) illustrates the rate of change of VRE penetration at each interval of wind installed capacity considered in the scenarios used in this study, with solar deployment levels displayed in the legend. For instance, considering 15 GW of solar capacity, every additional GW of wind installed from 20 to 25 GW, increases VRE penetration by 0.83 percentage points (PP). The rate of change with respect to solar is shown in Fig. 6 (b). To highlight the impact of curtailment, the same procedure has been followed with the VRE generation without curtailment, represented with black symbols (NC cases).

When curtailment is considered, the highest rate at which VRE penetration increases with additional wind capacity occurs at 20–25 GW of wind deployment. Without curtailment this rate would continue rising due to the higher average wind capacity factor resulting from the increase in offshore wind deployment. A similar trend is seen in the case of solar. However, the capacity factor of solar remains constant throughout the scenarios, thus as solar installed capacity increases the rate of change of penetration with an additional GW is directly offset by curtailment.

The larger reduction seen for wind reflects its higher correlation with curtailment, particularly at high wind installed capacity. Curtailment, therefore, reduces the marginal value of wind and solar capacity in terms of VRE penetration, consistent with findings in previous work [e.g. 45]. The effect that the technologies exert over each other can also be observed in the vertical separation of the dots for any given installed capacity on the x-axis in Fig 6. For both wind and solar, the presence of installed capacities of the other technology drives more curtailment. If curtailment is ignored, all the dots are on top of each other.

4.4. Impact on CO_2 emissions

Fig. 7. displays the annual CO_2 emissions of the power system, accounting for the emissions during operation, start-up and shut-down of conventional generators, which decrease from 61 $MtCO_2$ to 27.6 $MtCO_2$ per year predominantly as wind capacity is installed. This represents a reduction in the carbon intensity from the initial 181 gCO_2/kWh – when there are 15 GW of each technology – to 81.7 gCO_2/kWh – when the installed capacity of both technologies rises to 45 GW.

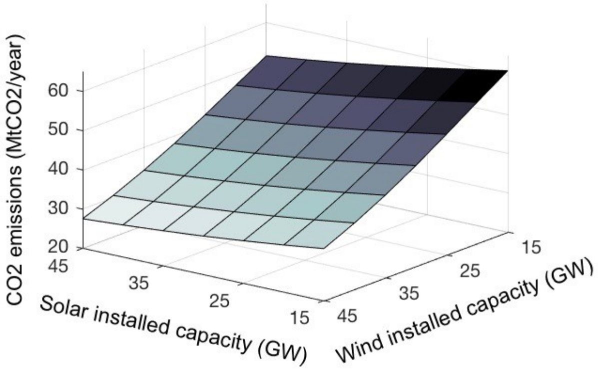
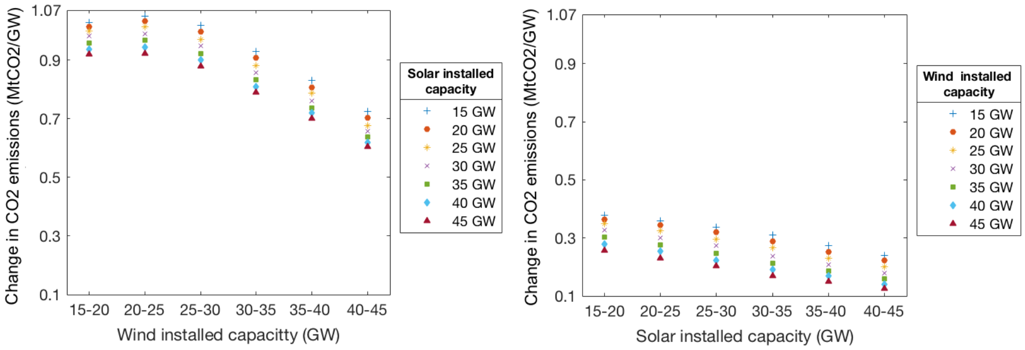


Fig. 7. System annual CO_2 emissions across all scenarios.

Another way of measuring the effect of curtailment is the rate of reduction of CO_2 emissions as more renewable capacity is installed, shown in Fig. 8. This relation is calculated following the same approach as in Section 4.3, by approximating the partial derivatives of the CO_2 emissions with respect to the installed capacity of each technology within limited bounds. For the detailed calculations refer to the supplementary material.



(a) (b)

Fig. 8. Change in emissions with every additional GW of (a) wind and (b) solar installed capacity.

The CO_2 emissions reductions achieved with additional installed capacity, i.e. the marginal value of capacity in terms of CO_2 savings, decreases as the levels of curtailment rise. This decrease is more accentuated as wind capacity is installed, driven mainly by the increase in curtailment. The initial increase in the rate of reduction stems from the combination of the increase in the average wind capacity factor and low levels of curtailment. Above 25 GW of wind, the increase in curtailment has a stronger influence on the rate of reduction of CO_2 emissions than the increase in the average wind capacity factor. This is displayed in a decreasing rate of reduction of CO_2 emissions. The lower capacity factor of solar is reflected in a smaller rate of CO_2 emissions reduction.

It can be seen that incremental CO_2 savings for higher levels of VRE deployment are lower than VRE penetration due to an increase in part-loaded conventional generators (that provide spinning reserve requirement) and in the number of shut-downs and start-ups of mid-merit plants (that accommodate variable penetration of renewables) in the system. The former are mainly associated with wind and the latter with solar generation, as shown in previous studies, including Hungerford et al. [8] modelling of the value of flexible load in the Australian National Electricity Market and a detailed study for NREL [46] that conducted operational analysis of the North American Western Interconnection for an illustrative year.

4.5. Case study

The previous sections quantified the levels of curtailment resulting from the minimum inertia floor. To showcase the effect of the inertial requirement, a case study evaluates the impact of the reduced inertia floor on the levels of curtailment and the value of wind contribution to the system flexibility via the balancing services, i.e. synthetic inertia and downward reserve. A medium-penetration scenario with 30 GW of wind and 30 GW of solar installed capacity is selected as a baseline case. This capacity, approximately double of the one in 2018, represents a plausible deployment to be achieved in GB in the medium-term. This scenario is also in line with the projections from BEIS [48], assuming 80% of the renewable generation is provided by wind and solar as in [49].

A reduced inertia floor of 70 GVA.s is considered, which is the unconstrained minimum level of inertia predicted by NGESO [5]. To maintain the new inertia level, a minimum load of 8.5 GW is approximated following the procedure introduced in Section 3.2.2.

Two cases are modelled:

1. Case A maintains the new minimum load solely with conventional generation.
2. Case B allows wind contribution to the minimum load:

$$D_{min,t} = L_{min,t} - S_i \cdot W_t \quad (12)$$

Wind contribution S_i is assumed to be 10% of the wind generation, which is the minimum volume indicated by NGESO for the provision of frequency response [50]. This modification to the initial minimum load constraint enables wind to contribute with 'synthetic inertia', reducing the need for inertia from conventional generation.

From cases A and B, an additional case is modelled to appraise the value of wind contribution to the downward reserve (wr). This is done by applying equation (4) introduced in Section 3.2.1 to both cases.

The results are illustrated in Fig. 9 and Fig. 10, which display the variations in annual curtailment and CO_2 emissions in comparison with the baseline scenario. Case A (section 4.5.1) evaluates the effect of a reduced inertia floor and Case B (section 4.5.2) considers the reduced inertia floor combined with the use of wind to provide synthetic inertia. Section 4.5.3 analyses the effect of using wind to provide downward reserve in cases A and B.

4.5.1 Case A - Reduced inertia floor

The reduction of the inertia floor drives a decrease in the annual curtailment by 3.98 TWh – a significant figure given that 5.3 TWh of curtailment were reached in the baseline scenario – with associated annual savings of around £200 million[5]. The increase in renewable penetration reduces annual CO_2 emissions by nearly 400 $ktCO_2$, albeit partially offset by the increase in the reserves and plant cycling and the reduction in emissions captured. The latter stems from a decrease in the time the plants retrofitted with carbon capture are operating (CCGT+PCC). Curtailment due to inertia decreases 4.3 TWh per year. Sequential curtailment – approximately 0.3 TWh/year – is now required to ensure conventional plants have sufficient foot-room to provide downward reserve. Wind sequential curtailment occurs mainly overnight in winter, when thermal plants would otherwise be running at their minimum load. Solar sequential curtailment takes place in the middle of the day during summer, as a result of the 'duck curve'.

4.5.2 Case B - Reduced inertia floor and wind synthetic inertia

When wind contributes to the minimum load by providing synthetic inertia, total curtailment is 76% lower than in the baseline scenario (reduced by 4.05 TWh per year) compared to 74.5% lower when wind does not provide synthetic inertia (case A). This represents a cost saving of approximately £210 million. This implies an increase in the annual VRE penetration by 0.1% when wind provides synthetic inertia, which is consistent with the findings of Teng & Strbac [16] in their evaluation of the potential system benefits from wind turbine's synthetic inertia in GB. While inertial curtailment reduces by 4.76 TWh, sequential curtailment more than doubles. The CO_2 savings achieved are however slightly lower than in Case A, close to 380 $ktCO_2$ annually, due to the increase in sequential curtailment.

4.5.3 Value of wind providing downward reserve

The previous cases have demonstrated that when the inertia floor is reduced, reserve requirements can increase curtailment – up to 0.8 TWh annually – in periods of low demand to maintain the foot-room held in conventional generators. Fig. 9 shows the change in curtailment when wind is allowed to provide downward reserve (wr). Annual curtailment is reduced by 4.3 TWh and 4.7 TWh in Case A (wr) and B (wr), respectively, compared to a decrease of 4.0 TWh in both cases when wind does not contribute to downward reserve. This represents a reduction of up to 88% on the total curtailment. Comparing case B (wr) (when wind contributes to both balancing services) with Case A (in which only the inertia floor is reduced), curtailment decreases by 722.6 GWh per year. This is solely due to wind contribution to synthetic inertia and reserves, and would involve annual savings of more

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[5] The associated curtailment costs in the baseline scenario are £272.74 million, considering the payments assumed in Section 3.2.3.

than £35 million. Associated savings compared to the baseline scenario are approximately of £220 and £240 million.

Sequential curtailment becomes zero in Case A (wr) and decreases by 91% in Case B (wr). The effect on the CO_2 emissions is however negligible (Fig. 10), since there is only a small decrease in part-loaded generators. This occurs because the units that are now being shut down instead of part loaded are mainly CCGT+PCC units that do not generate significant emissions, as seen in the reduction of the annual CO_2 captured. While expected, these results differ from the findings from Strbac et al. [18], since the changes in emissions are highly dependent on the system characteristics, e.g. renewable installed capacity and conventional fleet.

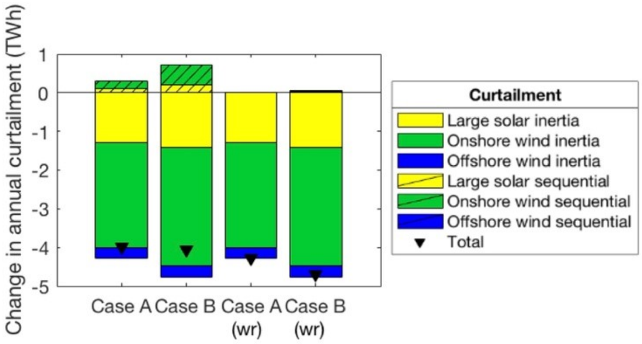

Fig. 9. Change in annual curtailment (TWh) in Case A, Case B and when wind provides reserves (wr) in comparison with the baseline scenario.

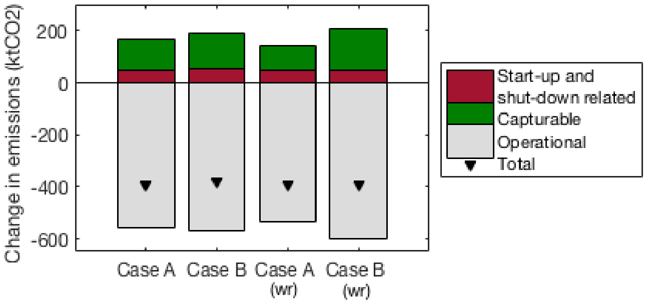

Fig. 10. Change in annual CO_2 emissions ($ktCO_2$) in Case A, Case B and when wind provides reserves (wr) in comparison with the baseline scenario.

Overall, this case study demonstrates the impact of inertia and reserve requirements on the levels of curtailment, and the value of wind contribution to the system flexibility via the balancing services. The reduction of the inertia floor is fundamental for a major reduction in curtailment, for which it is essential that distributed generation adapts to the new RoCoF limits. By allowing wind to provide synthetic inertia curtailment is further reduced, although the need for reserves still imposes a constraint on renewable penetration. This can be, however, reduced if wind turbines are allowed to provide regulating reserve. While occasional curtailments will increase as part of the Balancing Mechanism, allowing wind to provide reserves represents a more cost-effective approach than directly curtailing to hold these reserves in part-loaded thermal units.

These results suggest that the system flexibility required to cope with the increasing penetration of VRE and reduce curtailment could be mostly provided by a combination of a reduced inertia floor and facilitating increased flexibility in the operation of VRE technologies, reducing the need to invest in additional flexibility sources. It is thus important that the technical ability of wind – and solar – to provide these services is further investigated. Measures should also be developed to support the use of VRE flexibility in electricity systems.

5. Conclusions and further work

This paper models the integration of wind and solar generation in the future GB system. A unit commitment and economic dispatch model is used to simulate a broad range of scenarios of wind and solar installed capacity, including the operational constraints of the conventional generators and the requirements for system balancing. This represents a contribution to understanding the grid-scale impacts of wind and solar integration with a particular focus on quantifying the future levels of balancing-related curtailment and its impact on the VRE penetration and CO_2 emissions. This work proves the hypothesis that the most effective approach to reducing balancing-related curtailment is to address the inertial constraint, being able to decrease curtailment by 75%. The paper also evaluates the complementary approach to reducing VRE curtailment by allowing wind contribution to system balancing services – which shows reductions in total annual curtailment of up to 88%.

The results show that balancing-related curtailment increases predominantly as a non-linear function of wind installed capacity. For the GB test system modelled, this curtailment is mainly driven by the minimum inertia requirement, although curtailment to ensure foot-room availability also occurs when the inertia floor is reduced. The findings show that curtailment can add significant costs to the system balancing – reaching £1.8 billion per year at high installed capacities – if the current inertia limit is maintained. It is thus fundamental that the industry and the System Operator collaborate to successfully apply the new RoCoF limits.

The study finds that onshore wind has a stronger correlation with curtailment, albeit influenced by the levels of solar installed capacity, which depicts the importance of studying both technologies combined. Curtailment reduces the marginal value of capacity of both technologies in terms of renewable penetration and CO_2 savings. This might impact the renewable capacity needed to achieve the climate change targets and may affect the profitability of future projects that will not benefit from the government support payments.

A case study evaluates the impact of the reduction of the minimum inertia floor on the levels of curtailment, allowing also for wind contribution with synthetic inertia. The results show that while annual curtailment decreases by 76%, curtailment to guarantee foot-room availability for downward reserves increases up to 0.8 TWh per year. The value of wind contribution to the downward reserve is thus investigated, showing a reduction of the sequential curtailment to close to zero and reductions of the total annual curtailment by up to 88% with associated savings of £242.3 million. From the reduction in total curtailment, 14% stems solely from wind contribution to balancing, involving annual savings in excess of £35 million. These findings suggest that the flexibility needed to comply with the increasing VRE penetration could be addressed without necessarily investing in additional flexibility sources, if VRE technologies are allowed to participate in the provision of balancing services. It is thus important that the accessibility to the balancing markets is improved and that new products are developed to enable and incentivise VRE participation.

This work is also subject to several limitations that represent opportunities for further improvement. Additional flexibility sources such as storage systems or demand response constitute an important consideration for future studies, so as to complement the findings of this work and provide a holistic view of the likely evolution of curtailment in the UK. The inclusion of other renewable technologies that will potentially contribute to the achievement of the climate and energy targets in the UK should be considered in order to provide a complete vision of the future GB power system and investigate the effects of a combined technology mix. Finally, a thorough evaluation of the economic implications of the findings of this study remains essential to further illustrate the impacts of a high penetration of wind and solar generation in the UK, and thus represents a major area for future research.

Acknowledgements

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References

[1] International Energy Agency. Renewables 2017: Analysis and forecasts to 2022. OECD/IEA, 2017. URL, https://www.oecd-ilibrary.org/energy/renewables-2017_re_mar-2017-en.

[2] Pietzcker RC, Ueckerdt F, Carrara S, de Boer HS, Després J, Fujimori S, et al. System integration of wind and solar power in integrated assessment models: A cross-model evaluation of new approaches. Energy Econ 2016;64:583–99. doi:10.1016/j.eneco.2016.11.018.

[3] Kubik ML, Coker PJ, Barlow JF. Increasing thermal plant flexibility in a high renewables power system. Appl Energy 2015;154:102–11. doi:10.1016/j.apenergy.2015.04.063.

[4] Ma J, Silva V, Belhomme R, Kirschen DS, Ochoa LF. Evaluating and planning flexibility in sustainable power systems. IEEE Trans Sustain Energy, 2013. 200-209, doi:10.1109/tste.2012.2212471

[5] National Grid ESO. SOF System Operability Framework. 2016. URL, https://www.nationalgrideso.com/document/63476/download. .

[6] Ulbig A, Borsche TS, Andersson G. Impact of low rotational inertia on power system stability and operation. IFAC Proc. Vol., vol. 19, IFAC; 2014, p. 7290–7. doi:10.3182/20140824-6-ZA-1003.02615.

[7] Bird L, Lew D, Milligan M, Carlini EM, Estanqueiro A, Flynn D, et al. Wind and solar energy curtailment: A review of international experience. Renew Sustain Energy Rev 2016;65:577–86. doi:10.1016/j.rser.2016.06.082.

[8] Hungerford Z, Bruce A, MacGill I. The Value of Flexible Load in Power Systems with High Renewable Energy Penetration. Energy. 2019 Aug 20:115960. doi: 10.1016/j.energy.2019.115960

[9] Brouwer AS, Van Den Broek M, Seebregts A, Faaij A. Impacts of large-scale Intermittent Renewable Energy Sources on electricity systems, and how these can be modeled. Renew Sustain Energy Rev 2014;33:443–66. doi:10.1016/j.rser.2014.01.076.

[10] H. C. Gils, Y. Scholz, T. Pregger, D. Luca de Tena, and D. Heide, "Integrated modelling of variable renewable energy-based power supply in Europe," Energy, 2017. 123:173–188. doi:10.1016/j.energy.2017.01.115.

[11] Almenta MM, Member S, Morrow DJ, Best RJ, Fox B, Foley AM. An Analysis of Wind Curtailment and Constraint at a Nodal Level. IEEE Transactions on Sustainable Energy. 2017;8:488–95. doi:10.1109/TSTE.2016.2607799.

[12] Mc Garrigle E V., Deane JP, Leahy PG. How much wind energy will be curtailed on the 2020 Irish power system? Renew Energy 2013;55:544–53. doi:10.1016/j.renene.2013.01.013.

[13] Pfenninger S, Keirstead J. Renewables, nuclear, or fossil fuels? Scenarios for Great Britain's power system considering costs, emissions and energy security. Appl Energy 2015;152:83–93. doi:10.1016/j.apenergy.2015.04.102.

[14] Raugei M, Leccisi E, Azzopardi B, Jones C, Gilbert P, Zhang L, Zhou Y, Mander S, Mancarella P. A multi-disciplinary analysis of UK grid mix scenarios with large-scale PV deployment. Energy Policy. 2018 Mar 31;114:51-62. doi:10.1016/j.enpol.2017.11.062.

[15] Tielens P, Van Hertem D. The relevance of inertia in power systems. Renew Sustain Energy Rev 2016;55:999–1009. doi:10.1016/j.rser.2015.11.016.

[16] Teng F, Strbac G. Assessment of the Role and Value of Frequency Response Support From Wind Plants. IEEE Trans Sustain Energy, 2016;7(2):586–595. doi:10.1109/TSTE.2015.2505085.

[17] Joos M, Staffell I. Short-term integration costs of variable renewable energy: Wind curtailment and balancing in Britain and Germany. Renewable and Sustainable Energy Reviews. 2018 Apr 30;86:45-65. doi:10.1016/j.rser.2018.01.009.

[18] Strbac G, Aunedi M, Pudjianto D, Teng F, Djapic P. Value of Flexibility in a Decarbonised Grid

and System Externalities of Low-Carbon Generation Technologies. Imperial College London, NERA Economic Consulting 2015. URL, https://www.theccc.org.uk/wp-content/uploads/2015/10/CCC_Externalities_report_Imperial_Final_21Oct20151.pdf.

[19] Gupta A, Kumar A, Khatod DK. Optimized scheduling of hydropower with increase in solar and wind installations. Energy. 2019 Sep 15;183:716-32. doi.org/10.1016/j.energy.2019.06.112

[20] McPherson M and Tahseen S. Deploying storage assets to facilitate variable renewable energy integration: The impacts of grid flexibility, renewable penetration, and market structure. Energy 2018; 145:856-870. doi:10.1016/j.energy.2018.01.002

[21] Taibi E, del Valle CF, Howells M. Strategies for solar and wind integration by leveraging flexibility from electric vehicles: The Barbados case study. Energy. 2018 Dec 1;164:65-78. doi:10.1016/j.energy.2018.08.196

[22] Avagyan V, Bruce A, Stanojevic V. Dynamic Programming (DP) Unit Commitment (UC) MatLab Model. URL, https://gist.github.com/vitali87/ef958590fa507709a2ef9cc9ad08fe6a.

[23] Bruce ARW, Gibbins J, Harrison GP, Chalmers H. Operational Flexibility of Future Generation Portfolios Using High Spatial- and Temporal-Resolution Wind Data. IEEE Trans Sustain Energy 2016;7:697–707. doi:10.1109/TSTE.2015.2497704.

[24] National Grid. How we balance the country's electricity transmission system 2014. URL, https://www.nationalgrid.com/sites/default/files/documents/37790-ETYS%202014.pdf.

[25] Hawkins S. A High Resolution Reanalysis of Wind Speeds over the British Isles for Wind Energy Integration. Dr Philos Diss. University of Edinburgh, Edinburgh 2012. URL, https://www.era.lib.ed.ac.uk/handle/1842/7898.

[26] Pfenninger S, Staffell I. Long-term patterns of European PV output using 30 years of validated hourly reanalysis and satellite data. Energy 2016;114:1251–65. doi:10.1016/j.energy.2016.08.060.

[27] The University of Sheffield. Live PV generation 2017. URL, https://www.solar.sheffield.ac.uk/pvlive/.

[28] Department for Business Energy and Industrial Strategy (BEIS). Solar photovoltaics deployment: April 2017. 2017:Excel spreadsheet. URL, https://www.gov.uk/government/statistics/solar-photovoltaics-deployment.

[29] Department for Business Energy and Industrial Strategy (BEIS). Fossil Fuel Price Assumptions 2016. URL, https://www.gov.uk/government/publications/fossil-fuel-price-assumptions-2016.

[30] National Grid ESO. Future Energy Scenarios 2019. 2019. URL, http://fes.nationalgrid.com/media/1409/fes-2019.pdf.

[31] Bosch J, Staffell I, Hawkes AD. Temporally explicit and spatially resolved global offshore wind energy potentials. Energy 2018; 15;163:766-81. doi:10.1016/j.energy.2018.08.153.

[32] National Grid. Demand Forecasting. Reporting Period: 4th Dec 2017 – 11th Mar 2018. URL, https://www.nationalgrid.com/sites/default/files/documents/Quarterly%20Forecasting%20Report%20-%20March18.pdf

[33] International Energy Agency (IEA). Harnessing Variable Renewables: A Guide to the Balancing Challenge. 2011. doi:612011171P1. URL, https://webstore.iea.org/harnessing-variable-renewables.

[34] Li Y, Yang Z, Li G, Zhao D, Tian W. Optimal scheduling of an isolated microgrid with battery storage considering load and renewable generation uncertainties. IEEE Transactions on Industrial Electronics. 2018 Jun 1;66(2):1565-75. doi: 10.1109/TIE.2018.2840498

[35] Hodge BM, Lew D, Milligan M. Short-term load forecast error distributions and implications for renewable integration studies. IEEE Green Technol Conf 2013:435–42. doi:10.1109/GreenTech.2013.73.

[36] National Grid. Summer Outlook Report. 2017. URL, https://www.nationalgrid.com/sites/default/files/documents/8589939683-

2017%20Summer%20Outlook%20Report.pdf.
[37] Daly P, Flynn D, Cunniffe N. Inertia considerations within unit commitment and economic dispatch for systems with high non-synchronous penetrations. 2015 IEEE Eindhoven PowerTech, 2015. doi:10.1109/PTC.2015.7232567.
[38] Ashton PM, Taylor GA, Carter AM, Bradley ME, Hung W. Application of Phasor Measurement Units to Estimate Power System Inertial Frequency Response. Proc. IEEE Power and Energy Society General Meeting (PES), 2013. 1-5. doi:0.1109/PESMG.2013.6672671.
[39] Ela E, Gevorgian V, Fleming P, Zhang YC, Singh M, Muljadi E, et al. Active power controls from wind power: Bridging the gaps. National Renewable Energy Laboratory. 2014. URL, https://www.energy.gov/sites/prod/files/2014/01/f6/Active%20Power%20Controls%20from%20Wind%20Power.pdf.
[40] Vogler-Finck PJC, Früh WG. Evolution of primary frequency control requirements in Great Britain with increasing wind generation. Int J Electr Power Energy Syst 2015;73:377–88. doi:10.1016/j.ijepes.2015.04.012.
[41] Department for Business Energy & Industrial Strategy. Budget Notice for the Second CFD Allocation Round. 2017. URL, https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/598824/Budget_Notice.pdf.
[42] Barber J, National Grid. The Growth of Solar Power 2015. URL, https://www.nationalgrid.com/sites/default/files/documents/45627-05_Solar%20Growth.pdf.
[43] Gosden E. Balancing demand 'could cost National Grid £2bn’. The Telegraph. 2016 June. URL, https://www.telegraph.co.uk/business/2016/06/26/balancing-demand-could-cost-national-grid-2bn/
[44] Cook T, Shaver L, Arbaje P. Modeling constraints to distributed generation solar photovoltaic capacity installation in the US Midwest. Applied Energy. 2018 Jan 15;210:1037-50. doi:10.1016/j.apenergy.2017.08.108.
[45] Bistline JE. Economic and technical challenges of flexible operations under large-scale variable renewable deployment. Energy Economics. 2017 May 1;64:363-72. doi:10.1016/j.eneco.2017.04.012.
[46] Lew D, Brinkman G, Ibanez E, Florita A, Heaney M, Hodge B, et al. The Western Wind and Solar Integration Study Phase 2. 2013. URL, https://www.nrel.gov/docs/fy13osti/55588.pdf.
[47] Department for Business Energy and Industrial Strategy (BEIS). Updated Energy and Emissions projections 2016. 2017. URL, https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/599539/Updated_energy_and_emissions_projections_2016.pdf.
[48] National Grid. Future Energy Scenarios 2016. 2016. URL, http://fes.nationalgrid.com/media/1292/2016-fes.pdf.
[49] National Grid. GC022 - Frequency Response. 2013. URL, https://www.nationalgrid.com/sites/default/files/documents/16927-Workgroup%20Report.pdf.