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Impact analysis of supplementing solar generation sites with additional wind generation considering grid connection delays

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***Abstract*—Grid connection delays are currently causing significant issues for new renewable generation projects in Great Britain. The National Energy System Operator (NESO) has recently closed the connection queue to new requests, with over 700GW of new projects currently awaiting responses to connection requests. The average gap between requested and offered connection dates has increased to 5 years and despite an ongoing connection reform process the challenges faced by new renewable generation projects are putting net zero objectives at risk. In this paper, a novel techno-economic investigation is performed into the potential impact of increasing the generation capacity of a solar generation site through the addition of wind generation. The study considers varying time horizons for increased grid connections and how this impacts the levelized cost of energy (LCOE) and net present value (NPV) of the site. Results show positive implications with a 5 year connection delay, showing a possible reduction in LCOE of £1.86/MWh over a 20 year lifetime.**

***Index Terms*—connection delays, wind, solar, LCOE**

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I. Introduction

The Great Britain (GB) electricity grid is experiencing significant delays to new and increased connections being granted, with over 40% of new generation capacity installations having connection dates set at 2030 or beyond and the average connection delay between requested and offered dates increasing from 18 months to 5 years as of June 2024 [1]. This problem is not unique to GB, with similar issues being encountered across Europe with significant delays also being encountered in Italy, Germany and Spain as seen in Fig. 1 [2].

With new grid connection applications currently frozen [3] as part of the ongoing grid connection reform process in GB [4] there is an opportunity to analyse whether there is a benefit to installing additional generation at a pre-existing site without an immediate increase in the grid connection size. The over-installation of renewable plants has previously been shown to provide a positive economic impact, but mainly with the inclusion of battery energy storage and not in the context of considering delays in grid connection [5] [6].

This study examines the impact of grid connection delays

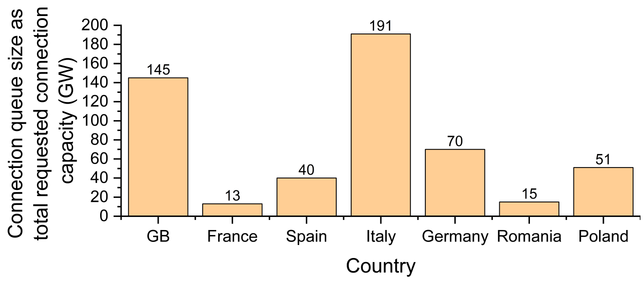

Fig. 1. Grid connection queues across Europe as total requested grid connection capacity [2]

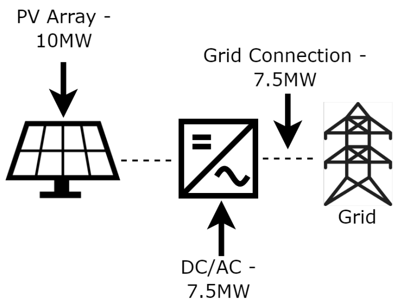

Fig. 2. Diagrammatic representation of initial site characteristics including selected variables

on the feasibility and effectiveness of increasing generation capacity at existing solar PV sites through the co-location of additional wind generation. A key focus is the identification of scenarios in which augmenting on-site generation capacity is advantageous, considering both the duration of grid connection delays and the scale of the additional capacity requested. Building upon the authors' previous work on unlocking potential in operational solar assets [7], this paper presents a novel analysis that, for the first time, explicitly incorporates the influence of grid connection delays into the decision-making framework.

II. Study Overview

In order to give a representative analysis of the most common existing solar generation site in the UK, the average generation capacity of 7.4MW has been used as a guide for the initial site [8]. Another key aspect is the solar inverter ratio (SIR), where the capacity of the solar PV array is oversized with respect to the power rating of the inverter. SIRs are generally found throughout the literature to be within the range of 1.2 to 1.4 [9]. It is calculated using Equation 1 where P_{pv} is the power rating of the solar installation in MWp and P_{inv} is the power rating of the inverter in MW. For the purposes of this study a 10MWp PV array installed with a 7.5MW inverter has been chosen with an SIR of 1.33. A diagrammatic representation of the site and the relevant specifications is shown in Fig.2.

$$SIR = \frac{P_{pv}}{P_{inv}} \tag{1}$$

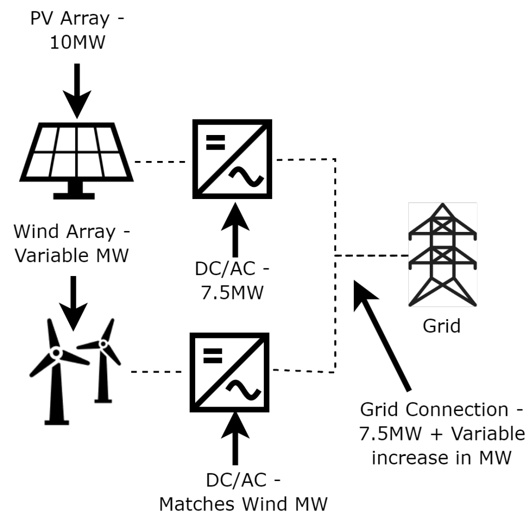

Fig. 3. Diagrammatic representation of proposed site characteristics including selected variables

For this study, different variables were chosen to explore the impact of changing the conditions for the installation of additional capacity. A diagrammatic representation of the site including wind generation is shown in Fig.3. The variables to be considered are; the capacity of the additional wind generation (P_w), the grid connection ratio (GCR) given by Equation 2, and requested increase to the grid connection (P_{new}). The GCR will be 1 if the increase in grid connection is equal to the rated capacity of the additional wind generation being installed.

$$GCR = \frac{P_{new}}{P_w} \tag{2}$$

A. System Charecteristics

There are multiple different economic aspects that need to be considered as part of this study. Firstly, the pre-existing solar capital cost is considered discounted according to the age of the solar installation, as given in Equation 3 where C_{pvb} is the capital cost of the original solar installation, A_{pv} is the age of the solar installation at the time of the study (assumed here to be 5 years unless stated otherwise) and L_{pv} is the design lifetime of the solar installation, assumed to be 20 years in this study.

$$C_{pv} = C_{pvb} \times (1 - \frac{A_{pv}}{L_{pv}}) \tag{3}$$

For the additional wind generation capacity, the wind installation capital cost C_w and the ongoing O&M costs for the wind generation are given in Table I, along with the ongoing O&M costs for the existing solar installation.

The electricity export price, C_{exp} is taken from the average value of the forward market prices in 2024, set as £79.30/MWh in this study [10]. Finally, the grid connection costs are split into fixed and variable tariffs and are shown in Table I [11].

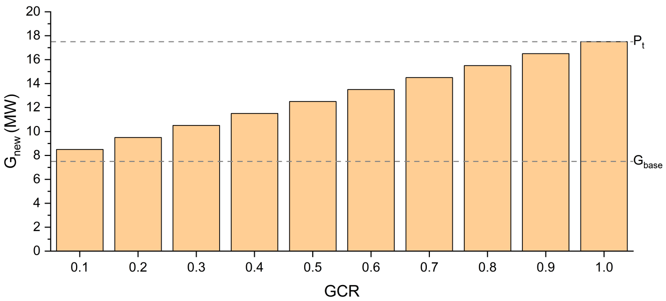

Fig. 4. G_{new} values for varying GCR when P_w = 10MW, P_{pv} = 10MWp, P_{inv} = 7.5MW and G_{base} = 7.5MW

TABLE I
COSTS ASSOCIATED WITH VARIOUS ASPECTS OF THE STUDIED SYSTEM

	£/kW		£/kW/yr		£/kW/day		£/MWh
C_w	1200	O_w	29	C_{fix}	65.8487	C_{exp}	79.3
C_{pvb}	620	O_{pv}	14.9	C_{var}	0.095		

The solar inverter ratio is set at 1.33 and the existing solar installation is set at 10MWp, giving an inverter rating (P_{inv}) of 7.5MW using Equation 4. The base site grid connection capacity (G_{base}) is set to match this at 7.5MW. The grid connection capacity for the new site is set using Equation 5. The new total power generation capacity of the site is calculated from Equation 6. An example of how G_{new} varies depending on the GCR for this base site is shown in Fig.4. This illustrates how lower GCR values will restrict the overall export capability of the site, whilst a GCR of 1 will allow the full power capability to be realised.

$$P_{inv} = SIR \times P_{pv} \tag{4}$$

$$G_{new} = G_{base} + GCR \times P_w \tag{5}$$

$$P_t = P_{inv} + P_w \tag{6}$$

B. Model

The model utilised in this study is shown in Fig.5, with the relevant variables used as inputs or produced as outputs included as defined in this paper. The system is implemented in MATLAB/Simulink. The inputs to the model are wind speed at 1-second resolution and recorded solar power output in kW, also at 1-second resolution. This study simulates 1 year of data from October 2023 to September 2024, with the calculated total energy generated subsequently exported to the MATLAB workspace for further analysis.

The model simulates three different scenarios concurrently;

- The energy generated by the base solar site
- The energy generated by the new site before a connection size increase is implemented
- The energy generated by the new site after a connection size increase is implemented

Fig.6 shows the power profiles of the new site (solar plus additional wind generation) before the requested connection capacity increase is in effect over a 7 day period. It can be seen that whilst some additional energy is exported from the site, particularly outside of normal solar generation hours, the 7.5MW connection size limits the export capability of the site with sharp peaks of 'lost' power occurring when the solar generation is at its peak.

Fig.7 shows the same site with an increased grid connection granted, which with GCR equal to 1 would result in the full rating of the additional wind generation (10MW) being added to the original grid connection capacity of 7.5MW. The 'lost' power over the same 7 day period is now zero as the site can fully utilise the increased connection capacity. However, the majority of the time is spent generating power significantly below the new site connection capacity of 17.5MW and suggests that lower GCRs could be more beneficial due to lower connection capacity costs.

C. Performance Metrics

The metrics Net Present Value (NPV) and Levelised Cost Of Energy (LCOE) are determined for the base site using Equations 9 and 8 where C_{base} is the yearly cost for the base site as given in Equation 7, E_{base} is the yearly energy generated by the base site, d is the discount rate, C_{pv} is the base site investment cost, I_{pv} is the yearly income for the base site, O_{pv} is the yearly O&M costs for the base site and X_{pv} is the yearly connection costs for the base site.

$$C_{baseyr} = O_{pv} + X_{pre} \tag{7}$$

$$LCOE_{base} = \frac{C_{pv} + \sum_{t=0}^{25} \frac{C_{baseyr}}{(1+d)^t}}{\sum_{t=0}^{25} \frac{E_{pv}}{(1+d)^t}} \tag{8}$$

$$NPV_{base} = -C_{pv} + \sum_{t=1}^{25} \frac{I_{pv} - C_{base}}{(1+d)^t} \tag{9}$$

The metrics modelling for the new site is achieved through a series of conditional equations to simulate the increase in connection capacity after a given number of years, termed t_{h}.

When calculating Net Present Value (NPV), Equation 10 determines the annual grid connection costs based on either the base grid connection size (G_{base}) or the upgraded connection size (G_{new}). The first term in the equation calculates the variable connection costs, scaled to an annual value by multiplying by 365 (days per year), while the second term accounts for fixed connection costs. This annual connection cost, denoted as X_w, is then used in Equation 12 to determine the ongoing yearly costs, along with the annual operations and maintenance (O&M) costs (O_w) listed in Table I. The additional capital expenditure associated with installing new wind capacity is calculated using Equation 13.

The annual revenue from exported electricity is calculated in Equation 11, where the energy generated before the grid

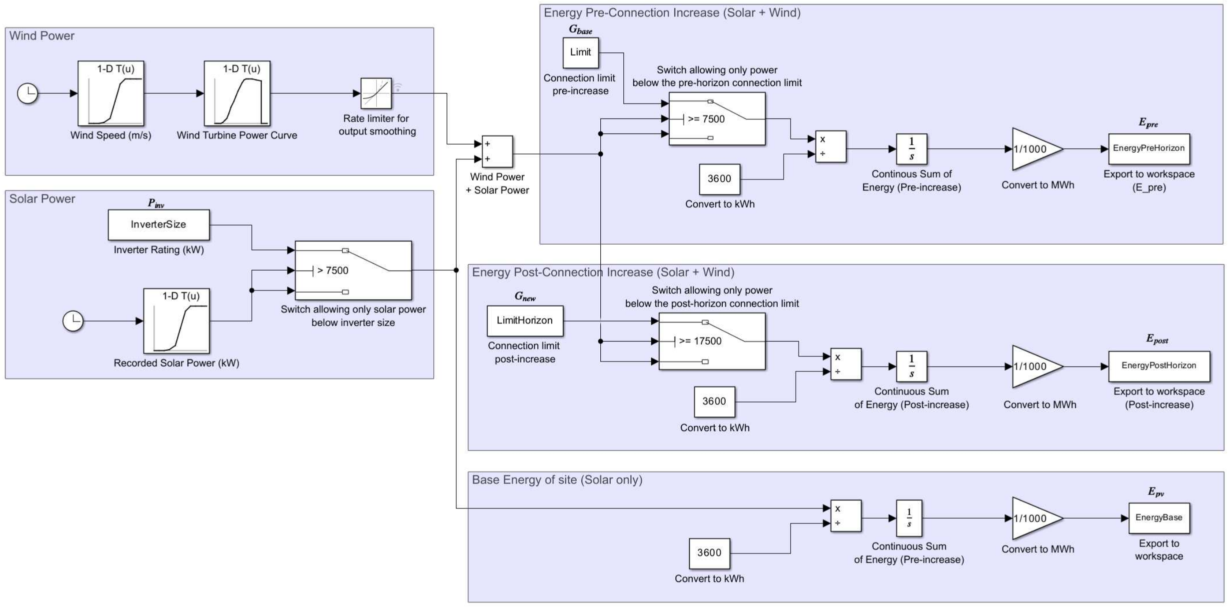

Fig. 5. MATLAB/Simulink model used in this study

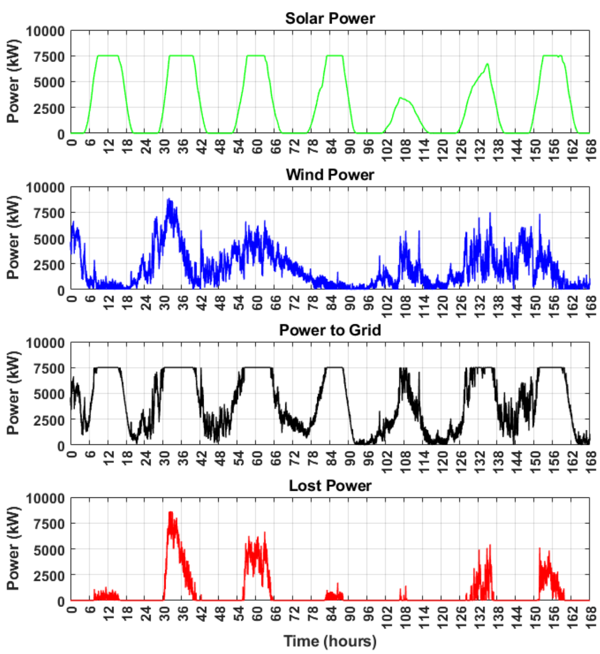

Fig. 6. Power profiles for Solar Power, Wind Power, Power transmitted to the grid and lost power due to grid connection size before the grid connection increase is in effect (P_w = 10MW, P_{pv} = 10MWp, P_{inv} = 7.5MW and G_{base} = 7.5MW)

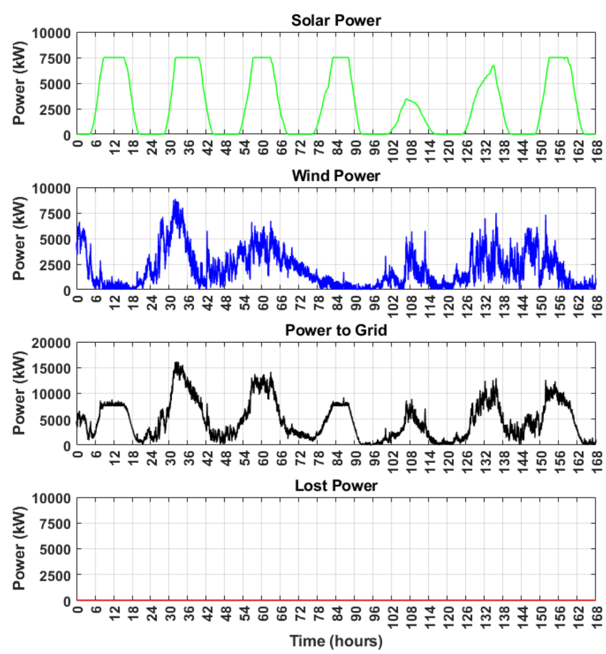

Fig. 7. Power profiles for Solar Power, Wind Power, Power transmitted to the grid and lost power due to grid connection size after the grid connection increase is in effect, with a GCR of 1 (P_w = 10MW, P_{pv} = 10MWp, P_{inv} = 7.5MW and G_{new} = 17.5MW)

connection upgrade (E_{pre}) is multiplied by the average export tariff (C_{exp}). After year t_h, the point at which the grid connection is upgraded, the post-upgrade energy output (E_{post}) replaces E_{pre} in the revenue calculation.

These cost and income values are then used in Equation 14 to calculate the NPV of the site following the connection upgrade. The improvement in value relative to the original configuration is then quantified using Equation 15. Additionally, the updated LCOE is calculated using Equations 16 and 17. For both Equations 16 and 11, E_{pre} and E_{post} represent the site's energy output before and after the grid connection increase, respectively. These energy values are derived from the MATLAB/Simulink model shown in Fig.5.

$$X_w = \begin{cases} 365G_{new}C_{var} + 365C_{fix}, & t > t_h \\ 365G_{base}C_{var} + 365C_{fix}, & otherwise \end{cases} \tag{10}$$

$$I_w = \begin{cases} E_{post}C_{exp}, & t > t_h \\ E_{pre}C_{exp}, & otherwise \end{cases} \tag{11}$$

$$C_t = O_w + X_w + O_{pv} \tag{12}$$

$$C_{new} = C_w P_w \tag{13}$$

$$NPV_{new} = -C_{pv} - C_{new} + \sum_{t=1}^{25} \frac{I_w - C_t}{(1+d)^t} \tag{14}$$

$$NPV_i = NPV_{new} - NPV_{base} \tag{15}$$

$$E_w = \begin{cases} E_{post}, & t > t_h \\ E_{pre}, & otherwise \end{cases} \tag{16}$$

$$LCOE_{new} = \frac{C_{pv} + C_{new} + \sum_{t=0}^{25} \frac{C_t}{(1+d)^t}}{\sum_{t=0}^{25} \frac{E_w}{(1+d)^t}} \tag{17}$$

III. RESULTS

Initial analysis was performed to investigate the effect of varying the proportion of additional wind generation capacity that is requested as increased grid connection capacity, referred to as GCR in this work. This approach operates under the same principle as utilizing different SIRs when installing solar generation, and is intended to determine if oversizing the additional wind generation in relation to the grid connection can achieve positive results.

A. *Varying additional wind generation capacity*

For this initial analysis, the grid connection delay was set at the current UK average of 5 years with an assumed lifetime of 20 years from installation date of the wind generation. The time at which the additional wind capacity is installed is considered as Year 0 in this study.

Fig.8 shows how the LCOE varies when varying capacities of additional wind generation are introduced, and at varying GCRs. As the GCR is lowered, the lowest available LCOE also decreases to a point, before beginning to rise again. The LCOE decreases in most cases compared to the baseline solar-only approach due to the additional energy generated by the added wind generation having a greater impact than the additional costs (such as capital, operation and maintenance, and grid connection fees).

The best available LCOE of £48.49/MWh (compared to a baseline £50.35/MWh for no additional wind generation capacity) is for a 0.3 GCR and a 5.5MW wind generation capacity deployed. In this scenario, the grid connection would be increased by 1.65MW to an overall capacity of 9.15MW. Whilst it may appear counterintuitive that decreasing the available grid connection capacity can lead to a lower LCOE, this result appears due to the additional wind generation being able to utilize the long periods of time where the solar generation is very low (primarily between dusk and dawn). As an increased size of grid connection results in additional costs, the additional energy generated by using higher GCRs is outweighed by the increase in grid connection costs in certain scenarios.

Whilst LCOE is an important metric for renewable generation, it does not account for the revenue generated by the energy being exported. Because of this it is important to also consider the NPV of the system, highlighted in Fig.9. This figure shows that whilst there are significant LCOE improvements to be achieved at low GCRs (as seen in Fig.8), these low GCR values result in declining NPV increases as the wind generation capacity is increased whilst the higher GCR values continue on an upward trend, and begin to decrease at much higher values than the lower GCR scenarios. This is due in part to the existing solar generation becoming a much smaller ratio of the overall site compared to the additional wind generation. This suggests that there are trade-offs available between achieving a lower LCOE whilst also increasing the NPV of the site.

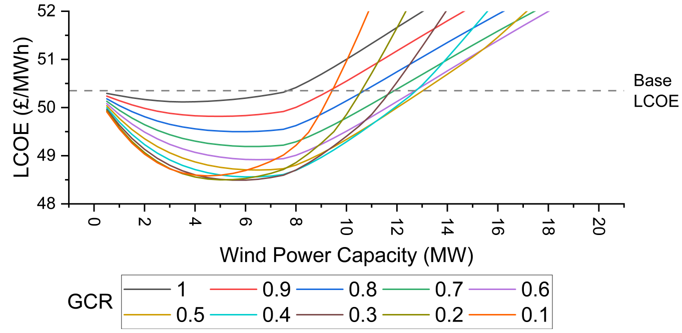

Fig. 8. LCOE for varying GCRs across a range of different additional wind generation capacity values

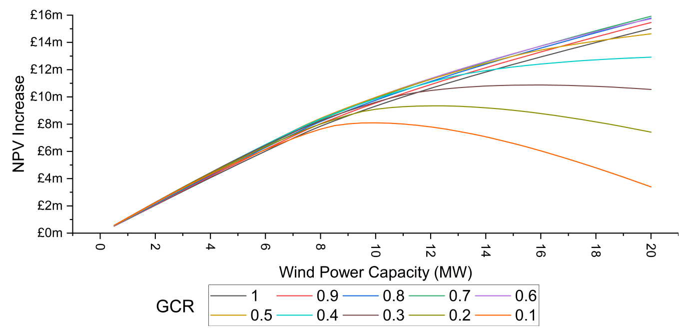

Fig. 9. NPV for varying GCRs across a range of different additional wind generation capacity values

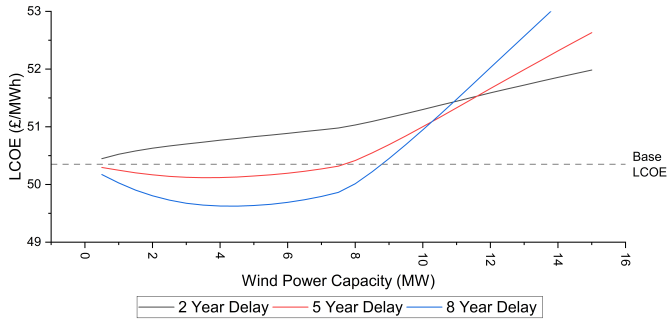

Fig. 10. LCOE for varying additional wind generation capacity and grid connection delays, with GCR = 1

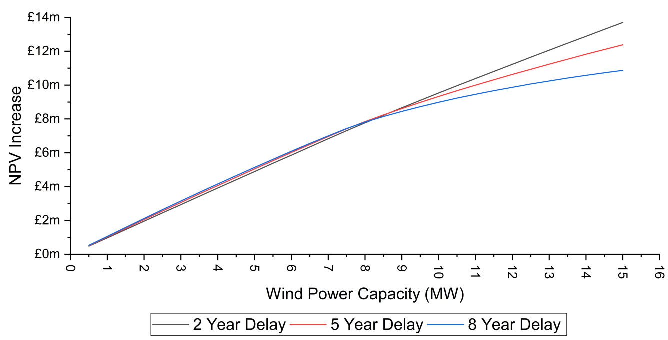

Fig. 11. NPV for varying additional wind generation capacity and grid connection delays, with GCR = 1

B. Varying grid connection delay

Following on from this, further analysis was conducted to assess the effect of varying the delay to the increased grid connection being granted. The delay was varied between 2, 5 and 8 years with a GCR of 1 to provide initial results on the effects that shorter or longer delays have on the economic viability of the proposed system.

Fig.10 shows the effect of varying grid connection delays on the LCOE of the system. A 2-year delay has a significant negative impact on the suitability of adding additional wind generation, suggesting no positive impact when compared to making no modifications to the base solar generation site. However, as the grid connection delay is increased there is a more positive impact, as the additional wind generation capacity utilises the cheaper grid connection for a longer period of time. However, as the additional wind generation capacity is increased too far, the LCOE begins to increase, due to the existing connection capacity saturating.

The opposite trend can be seen in Fig.11 where a shorter delay results in a higher NPV increase, however, this only occurs once the additional wind generation capacity begins to exceed 9MW. Before this point, there is minimal effect in varying the grid connection delay time. This trend occurs because when considering the NPV, it is more important for the additional wind generation at higher powers to begin generating to the full capability as soon as possible.

IV. Conclusions

This study has presented a first investigation of the potential for supplementing existing solar generation with additional wind generation capacity when considering grid connection delays for increased capacity.

It has been shown that improvements to both LCOE and NPV can be achieved by installing additional wind generation capacity despite a studied grid connection delay of 5 years. However, it has also been shown that installing excessive additional capacity will result in negative economic impacts.

The trade-offs between reducing LCOE and increasing NPV have also been examined, demonstrating that these two economic metrics can yield significantly different assessments of a project's viability. This divergence highlights the need for further investigation, particularly through the application of multi-objective optimisation techniques aimed at identifying an optimal balance between the two metrics.

The results shown in this work can have a positive impact on the ability for additional renewable generation to be deployed for the GB grid whilst connection reforms are taking place, mitigating the impact of grid connection delays.

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