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DISCUSSIONS

Flexible Wind Farm Control: A Review of Wind Power Participation in Future Power Systems

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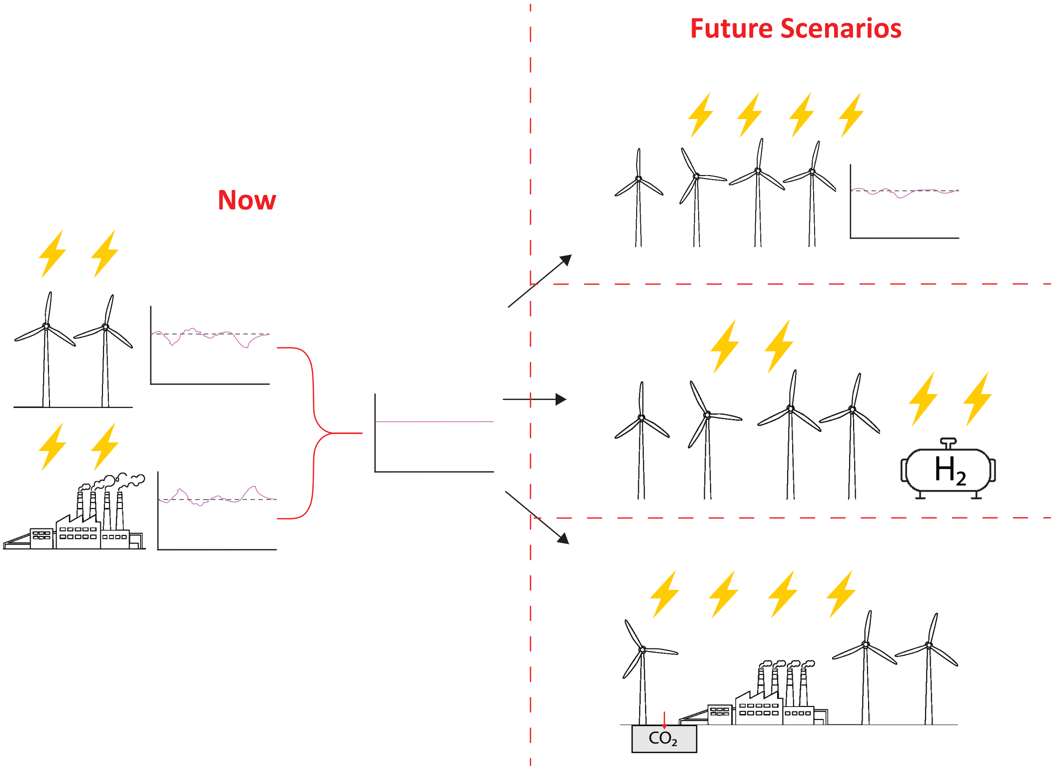
Abstract. Conventional wind farm operation, which prioritises power maximisation, is poorly aligned with the evolving requirements of modern power systems, characterised by increased asynchronous generation and reduced dispatchable capacity. This review uses Flexible Wind Farm Control as a term that encompasses control techniques that intentionally modulate wind farm output to better integrate wind energy with the grid. Focusing on European and UK contexts, the review examines how current policy frameworks, market structures, and system-needs are driving demand for new sources of flexibility. A comprehensive review of the literature is presented, covering key application areas of Flexible Wind Farm Control including frequency control, voltage support, fault ride-through, and integration within co-located and hybrid energy systems. Particular attention is given to rotor-side control strategies enabling power set-point tracking, synthetic inertia provision, and reserve-based operation. The review highlights differences in objectives, time scales, and system interactions for Wind Farm Control strategies that prioritise grid support over power maximisation. However, inconsistencies between policy and the recognised role of wind energy in providing flexibility remain clear. At the same time, much of the existing literature relies on simplified modelling approaches, highlighting the need for higher-fidelity models of turbine and farm dynamics, including turbulence, wake effects, and component fatigue, to better asses the performance of Flexible Wind Farm Control strategies. Overall, the literature suggests a persistent gap between policy and the technical capabilities of Flexible Wind Farm Control. Although some policy makers have acknowledged the potential of wind farms to support flexibility, significant work is required to fully identify and implement these capabilities in future power systems. Going forward, increased data availability, higher-fidelity simulation results, and field studies will be essential to establish wind farms as reliable providers of power system flexibility.



1 Introduction

The global energy transition is increasingly driven by the large-scale deployment of wind and solar power, as a direct result of international and regional policy targets aimed at reducing emissions by increasing the participation of renewable energies in power systems (United Nations, 2015; DESNZ, 2025). Many countries are failing to meet their climate commitments, adding pressure to develop renewable generation at an accelerated rate in the approach to Net-Zero 2050 (DNV, 2025). As a result, renewable energy is seeing significant development. The energy think tank Ember reported that renewables have become the leading source of global electricity for the first half of 2025 and contributed to more than a third of global electricity generation throughout 2025 (Wiatros-Motyka and Rangelova, 2025; Fulghum et al., 2026).

Despite the benefits, the variability and non-dispatchable nature of renewable energy has led to challenges within power systems, which have had to respond to the non-dispatchable variability by increasing flexibility across the rest of the system. Traditionally flexibility is an inherent characteristic of rapidly dispatchable generators, especially gas and hydro, as well as energy storage and grid services which together provide this support. With the resultant decrease in dispatchable generation due to the energy transition, the primary concern for power systems is shifting from power availability to providing additional flexibility elsewhere (DESNZ et al., 2025; ENTSO-E, 2023).

Variable renewable energy sources do not boast the same inherent flexibility as their carbon intensive counterparts. Therefore, increased renewable penetration would require significant infrastructure investment, which is not only costly but also slow to

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implement. The absence of dispatchable alternatives highlights the need for control techniques outwith the traditional methods for renewable energy.

Traditionally, control of wind farms has focussed on maximising generation, cementing them as a competitive option against fossil fuels. The evolving needs of power systems have exposed that maximising generation may be too narrow a goal, and broader requirements should be defined. Research has explored how wind turbines can be operated to provide ancillary services to grids (Cole et al., 2023; Eguinoa et al., 2021; Ullah et al., 2023). Rather than maximising their power, turbines can regulate their output to meet grid needs.

In this review, the term *Flexible Wind Farm Control* (FWFC) is used as a descriptive term to collate existing research in which wind farms are operated in a way to provide grid support and system flexibility. FWFC includes both mechanical (rotor-side) and electrical control strategies across multiple timescales that support the integration of wind energy, such as through ancillary markets. The use of the term FWFC enables consistent discussion across fragmented literature and clearer identification of research gaps.

To maintain stability and meet the needs of the grid, Transmission System Operators (TSOs) have many 'tools' at their disposal, which allow them to maintain the balance of the grid. One of these tools is curtailment. Curtailment is the act of reducing the power output of a generator, which particularly affects renewable generators, as high renewable energy output does not always align with high demand (Drax, 2022). There are two main forms of curtailment; economic curtailment, and technical curtailment. Economic curtailment, as its name suggests, is driven by purely economic reasons. Operators may decide that it is not financially viable to produce the maximum power output available, due to, for instance, negative wholesale prices agreed in the relevant market. Technical curtailment is the reduction in output power due to requests from the TSO, typically due to constraints on export power. In order to reduce unnecessary curtailment, the EU introduced a more dynamic day-ahead market, moving from hourly to 15-minute trading intervals (Directorate-General for Energy, 2025). By pricing electricity in shorter windows, market prices can better reflect real-time supply and demand conditions, reducing instances where operators face negative prices and choose to curtail economically, only for technical curtailment to be mandated shortly after.

During the balancing period, technical curtailment may be required if the demand is lower and/or the renewable generation is higher than anticipated, or there is a lack of transmission capacity between the sources of supply and demand centres. Considering the UK, the majority of wind generation is in Scotland, while demand is largely in England. As a result, wind farms are frequently curtailed in Scotland in the event of a transmission constraint, whilst the output of gas turbines increases in England to meet demand (Storey et al., 2025). As technical curtailment is mandatory and dictated by the TSO, operators are typically compensated for technical curtailment, although these payments depend on country-specific policies. In the case of the UK, payments are typically equivalent to their CfD strike price (Drax, 2022; Synertics, 2024). Currently, these constraint payments make up the majority of balancing costs for the UK grid, partly paid to the operators being curtailed but also increasingly to the operators of gas generators to cover the energy lost to curtailment (NESO, 2025a).

Wind turbines are often gathered in farms, usually with a single point of connection to the grid. Thus, it is reasonable to consider a wind farm as a single entity that can be controlled for a common goal. This is called *Wind Farm Control* (WFC). Much of the work in this area has focussed on power maximisation through *Wind Farm Flow Control* (WFFC), which is the act of controlling wind turbines to manage wake interactions within the farm (Andersson et al., 2021; Dong et al., 2022). Typically, when discussing Wind Farm Control, only WFFC is considered as it constitutes such a large proportion of the literature, though it is only one of a larger portfolio of Wind Farm Control options. This review considers WFC options other than WFFC – for information on WFFC readers are directed to Andersson et al. (2021); Stock et al. (2024); Dong et al. (2022); Meyers et al. (2022); Eguinoa et al. (2021) – and instead focusses on FWFC, as defined earlier. Current research varies widely in its assumptions and modelling fidelity. Studies often focus on individual services, giving limited attention to multi-service approaches and their co-ordination. Thus, it is difficult to assess the feasibility and potential of wind farms to implement these strategies.

This paper outlines the growing need for grid stability and flexibility in section 2 and considers the policies and markets within European (EU) and UK grids in section 3, with the primary focus on the UK system due to the high volume of wind penetration and data availability. Current literature on the use cases for Flexible Wind Farm Control is reviewed in section 4, with a focus on what can be achieved through the mechanical (rotor side) control of turbines, alongside a discussion of the key differences between WFFC and FWFC. With the foundation set, we can then explore the uses of FWFC in more depth in section 5, with a summary of identified research gaps in section 6. Before presenting the final conclusions in section 7.

2 Grid Operation

TSOs are responsible for maintaining the balance between the supply and demand of the grid, which was historically achieved by ramping up or down fossil fuel-based generators. Poor demand balancing, be that through imperfect load or generation prediction or through faults, can lead to deviations in system frequency and voltage. Such deviations beyond safe limits could result in damage to equipment or the disconnection of generators for their protection, which could then cascade, leading to a blackout. The UK grid operates at a nominal frequency of 50 Hz within a legal limit of ± 0.5 Hz unless there are exceptional circumstances. To maintain a safe operating range or return to a safe operating range after a deviation, NESO, the UK's TSO, requires plant to remain operational and connected to the grid, as summarised in Table 1. To discuss the growing need for grid stability, the issue of flexibility is first defined within section 2.1, before the current strategies for managing stability are described in 2.2.

2.1 Flexibility

Here, the flexibility of an energy system is defined by its ability to maintain the energy balance. There are two main areas of flexibility depending on its source, which are supply-side flexibility and demand-side flexibility. Supply-side flexibility, is the ability to adjust supply to meet demand. Demand-side flexibility involves consumer side participation through adjustment of flexible demands such as heat pumps and electric vehicles (Golmohamadi, 2022). From the supply-side, there are numerous different optional and mandatory mechanisms that allow generators to contribute to the overall stability of the grid. However wind energy is not typically well placed to participate in these mechanisms.

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Table 1. Range of the routine system frequency for the GB grid, together with requirements on operation time for plant and apparatus (NESO, 2025e).

Frequency Range	Circumstances	Requirements
49.5 Hz – 50.5 Hz	normal range	
Operating requirements		
51.5 Hz – 52.0 Hz	Exceptional	At least 15 minutes
51.0 Hz – 51.1 Hz	Exceptional	At least 90 minutes
49.0 Hz – 51.0 Hz	Typical	Continuous operation
47.5 Hz – 49.0 Hz	Exceptional	At least 90 minutes
47.0 Hz – 47.5 Hz	Exceptional	At least 20 s

In a renewable dominated grid, flexibility becomes much more of a challenge (DESNZ et al., 2025). Renewables such as wind depend on environmental conditions — which are inherently variable and difficult to predict — making balancing the grid much more complicated. Traditionally operated renewable energy generators do not operate flexibly as financial incentives favour power maximisation, leaving no room for reserve generation. In times of surplus wind energy, there are few options other than to curtail output. Flexibility can be provided using energy storage to divert excess generation within the installed storage capacity, however there are large cost implications in the construction and operation of the necessary storage.

As a supply-side flexibility strategy for wind farms, the curtailment process can take different forms depending on requirements and controller design. Whether by switching turbines off entirely or through partial curtailment of multiple turbines. Although both methods can achieve the same end goal, there are likely differences in the impact on turbine loading and lifetime as a result of differences between turbines that are stopped and started repeatedly versus the use of a different control method.

2.2 Stability

An overview of grid stability requirements and the typical markets in which generators participate to ensure stable operation of the wider power system is provided in the following sections. The different requirements are classified by their required response time, and their associated markets are described in sections 2.2.1 – 2.2.2. The UK and Danish markets, with their TSOs NESO and Energinet, have been chosen for this work as they have high degrees of renewable penetration and represent both EU and non-EU markets.

Another tool for TSOs is Fault Ride Through (FRT), which, similarly to curtailment, is a requirement for generators to participate in. FRT requires generators to remain connected and participate in fault recovery. The exact details are outlined in the grid codes (NESO, 2025e; MYEN, 2024). In the UK the requirements are for generators to stay connected to the grid for faults of up to 140 ms and restore active power to at least 90 % of its pre-fault level within 0.5 s of it being restored. In addition to mandatory requirements, there are a number of services and ancillary markets in which generators can participate.

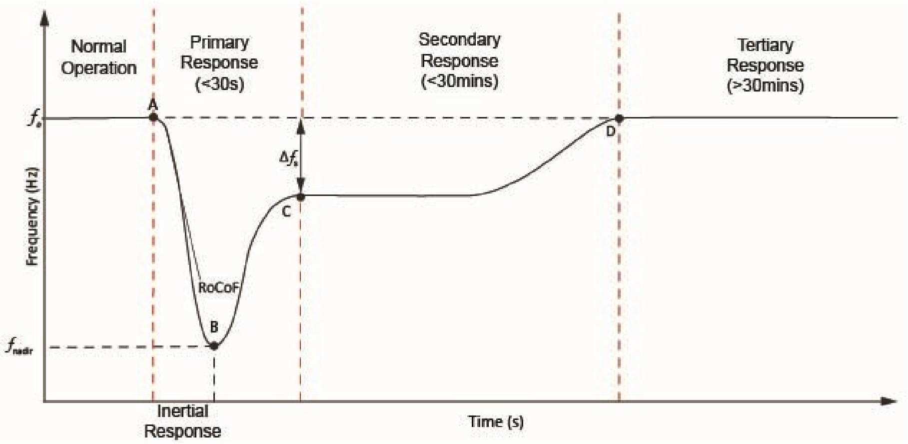

Figure 1. Typical frequency response curve

Participation in these markets allows generators to contribute to the overall stability and reliability of the grid. Some of these services are described below and discussed in the sections that follow (NESO, a).

2.2.1 Primary and Secondary Response

Given that a wide variety of terms are used to refer to frequency response across academic and industrial spaces, it is important to define them clearly. The most common terms seen for frequency response within the literature are illustrated in Fig 1. In the event of a fault there is typically an inertial response which lessens the impact of the fault (A-B), primary frequency control (B-C) is then used to stabilise the system frequency. Secondary frequency control (C to frequency restoration) then stabilises the frequency at some intermediary value while restoring the primary reserves. Finally, tertiary control is used to restore depleted secondary reserves to prepare for future faults (Socomec).

The first protection against large frequency deviations is "Fast Frequency Response" (FFR), which reduces the impact of a fault and decreases the nadir (Socomec). Denmark's TSO, Energinet, uses the same terminology while NESO includes it within their "Dynamic Containment Services". NESO defines two categories of frequency response. "Dynamic response", which adjusts to second-by-second frequency changes, and "non-dynamic response", which only occurs when frequency exceeds a certain limit. Primary and secondary frequency control are classified as part of the Mandatory and Commercial frequency response services outlined by NESO. Comparatively, Energinet – which operates in both the EU and Nordic markets – uses narrower categorisations defining strategies by their response speed and total energy delivery (Energinet). The common terminology used within the literature will continue to be used throughout this paper and the industry equivalents are summarised in Table 2. Tertiary control is included as a frequency service by Energinet, called manual Frequency Restoration Reserve, while NESO includes it within their reserve services.

Table 2. Comparison of typical academic terminology with terminology used in the UK, EU, and European markets (NESO, 2025c, d, b)

Principle	UK	EU
Fast Frequency Response	Dynamic Containment	FFR (Nordic market only)
Primary Control	Mandatory/Commercial Response	FCR
Secondary Control	Mandatory/Commercial Response	aFRR
Tertiary Control	Reserve Service	mFFR

2.2.2 Tertiary Response and Reserve Services

There is no way to know exactly what the energy demand or generation (mainly wind and solar) will be at any given moment. Which, poses a problem for TSOs. If supply is unknown, and demand is unknown, how can the grid be balanced? Forecasting and reserve services can play a role in resolving this dilemma. Forecasting is not the focus of this review, but an understanding of how current markets operate and the fundamentals of currently used forecasts is essential to understand how TSOs make their decisions, particularly when to replenish and empty reserves.

There are numerous forecasting techniques which can be broadly classified depending on their time scale (long term or short term) or whether the model is data driven or not (black-box or white-box). Short term forecasts are used primarily for balancing, while long term forecasts can be used for investment or policy purposes (Kazmi and Tao, 2022). As power systems move away from the largely predictable traditional generation, generation forecasting is necessary to ensure stability. Using estimates of both available power and demand, the TSO can then issue requests for generators to perform certain actions such as curtailment or the co-ordination of reserve capacity (Goodarzi et al., 2019).

Reserves are backups for when there is an unexpected imbalance between the supply and demand of the system. Reserve services can be provided in the form of flexible generation or flexible demand (NESO, c; Goodarzi et al., 2019). The primary purpose of reserve services is to maintain the frequency of the grid in case it is not possible to balance supply and demand with available generators and demand side management alone. This is reflected in the ancillary service markets that Energinet presents as options for operators on both the European and Nordic grid markets (Energinet). Energinet buys reserves through their capacity market using a bidding system. If a bid is accepted, the stakeholder is paid to offer their services if needed, requiring them to also bid on the energy market, which is usually optional. The UK on the other hand, has dedicated reserve services which are distinct from their frequency services. NESOs reserve services operate similarly to Energinet's capacity market, where generation is acquired ahead of time, such as balancing reserves. Forecasting methods can be unreliable and cannot predict faults, so NESO also includes many on the day services, each having their own technical requirements and reimbursement schemes, which are outlined in depth on NESO's industry information page (NESO, a).

3 Policy

The global push for net-zero was kickstarted by the Paris agreement, in which 195 countries pledge to limit the global average temperature rise to 2 °C of pre-industrial levels (United Nations, 2015). Out of all the countries that signed the Paris agreement, only six (3 %) have reduced their emissions in accordance with their initial pledges. Based on annual forecasts carried out by DNV, the world will not reach their net-zero goals, despite the Paris agreement being a legal obligation (DNV, 2025). Although the world is falling behind, some countries and governing bodies are still striving to achieve their pledges. Given the global scale and regionality of the problem the focus of this review has been placed on policy within the EU and UK. First, the commitments of the EU and the future outlook for its energy system are reviewed in section 3.1, noting that the EU remains the fourth largest carbon dioxide emitter (Climate Watch). Next, a closer look at the progress of the UK and its plans towards its net-zero targets is presented in section 3.2.

3.1 EU

The EU sets the overarching policies and targets for their member states, which is the responsibility of the individual nations, via the appropriate TSOs to follow and actively enable. The energy mix of the EU is dominated by low-carbon sources, providing 71 % of the electricity consumed. Approximately 60 % of electrical consumption in the EU comes from wind, solar, and hydropower (Low Carbon Power, 2025). On their path towards being carbon neutral by 2050, the EU aims to reach net reductions of 55 % by 2030 and between 66.25 and 72.5 % by 2035 compared to 1990 levels (Council of the EU, 2025).

All of the EU TSOs, and much of Europe outwith the EU operate together under the *European Network of Transmission System Operators for Electricity* (ENTSO-E), which oversees the operation of much of the European energy market. ENTSO-E are a collective of 40 TSOs from 36 countries operating under EU based legislation, whether or not they are a member of the EU (ENTSO-E, a). They play a vital role in contributing to wider EU policy by bringing together expertise and knowledge from multiple countries. Using its extensive network, ENTSO-E develops the Ten-Year Network Development Plan (TYNDP), which outlines how the European power system can navigate the net-zero transition (ENTSO-E, a, b). A study of the EUs system-needs conducted as part of the TYNDP in 2022 discussed the challenges created as a consequence of the energy transition (ENTSO-E, 2023). The report identified several challenges, including the growing need for greater flexibility in generation, demand, and infrastructure as a result of the decrease in system inertia from distributed generation and renewable energy.

Flexibility is becoming an increasingly important topic as countries around the world accelerate towards achieving net-zero. The EU has specifically acknowledged the need for improved system flexibility as a stepping stone to achieve their climate goals (Dedecca et al., 2025). Dedecca et al. (2025) reviewed both technologies and policies that can facilitate a safer transition and increase flexibility within the EU energy system. It was deemed that the majority of the EU's flexibility has come in the form of fossil fuel based dispatchable generation and pumped hydro. Without fossil fuels there is limited flexibility in the current mix of nuclear and renewables, making further research and investment essential. In particular, the study highlighted the need for "system-friendly renewable energy generation" to reduce the need for flexibility or even actively provide it.

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Table 3. The potential of different flexibility sources to address the needs of the European transmission network (ENTSO-E, 2022) (● = Most promising, ○ = Contributing).

Category	Source	Periods of vRES shortage	Balancing/ congestion	Stability/ inertia	Voltage control	Reliability/ restoration
Generation	Hydrogen power gen.	●				○
	Dispatchable RES	●	○	○	○	●
	Variable generation		●	●	●	○
Grid	Interconnections (HVDC)	●	●	○	●	○
	Grid flexibilities		●	●	●	●
Storage	Chemical batteries / V2G		●	●	●	●
	Supercapacitors			○		
	Hydro pumping storage	○	●	●	●	●
	Flywheels			○		
	LAES/CAES, thermal	○	○	○		
Power-to-X	Power-to-hydrogen		●	○	○	
	Power-to-heat		○	○		
Demand	Smart charging / DSR	○	●	●	○	○
	Large DSR	○	●	●	○	●

A cost benefit analysis carried out in the context of Germany's power system, proposed wind turbines, and solar PV as cost-effective options for flexible operation within the German system, particularly for ancillary services (Ackermann et al., 2024). Dedecca et al. (2025) suggest that curtailment, while being a cost-effective strategy for local flexibility, should not be used in response to grid constraints, instead investments in grid expansion or co-location should be used. Although batteries and energy storage systems (BESS) can be effective in reducing curtailment volumes, they will never eliminate the problem due to factors limiting storage size, such as capital costs. A summary of the identified requirements (needs) and solutions (sources) is provided in Table 3, which shows that increased generation flexibility is capable of addressing the evolving system needs throughout the energy transition.

3.2 The UK

The following section provides an overview of the current UK grid, to evaluate the role that wind energy can play in future power systems, followed by future grid scenarios for what the grid may look like post 2030. It is essential to understand the current structure of the UK's grid, policies, and regulations along with future scenarios set out by regulatory bodies, such as the UK Government's *Department for Energy Security and Net Zero*, DESNZ.

The UK network is a mixture of fossil fuels, nuclear, and renewable energy sources, with wind energy contributing significantly to total capacity. In 2024 wind energy became the largest source of electricity generation for the first time, accounting for 30 % of total generation, with gas following closely behind at 26.3 % (NESO, 2025b; National Grid, 2024). NESO are

Table 4. The future pathways to net-zero defined by NESO and their definitions (NESO, 2025d)

Scenario	Description
Holistic Transition	High consumer engagement and supply-side flexibility with the highest proportion of renewables and little hydrogen for dispatchable power
Electric Engagement	High supply-side flexibility with large amounts of nuclear, renewables, bioenergy and CCS
Hydrogen Evolution	High levels of dispatchable hydrogen plants which reduces the need for renewables and nuclear
Falling Behind	Some progress is made towards net-zero but is ultimately not sufficient

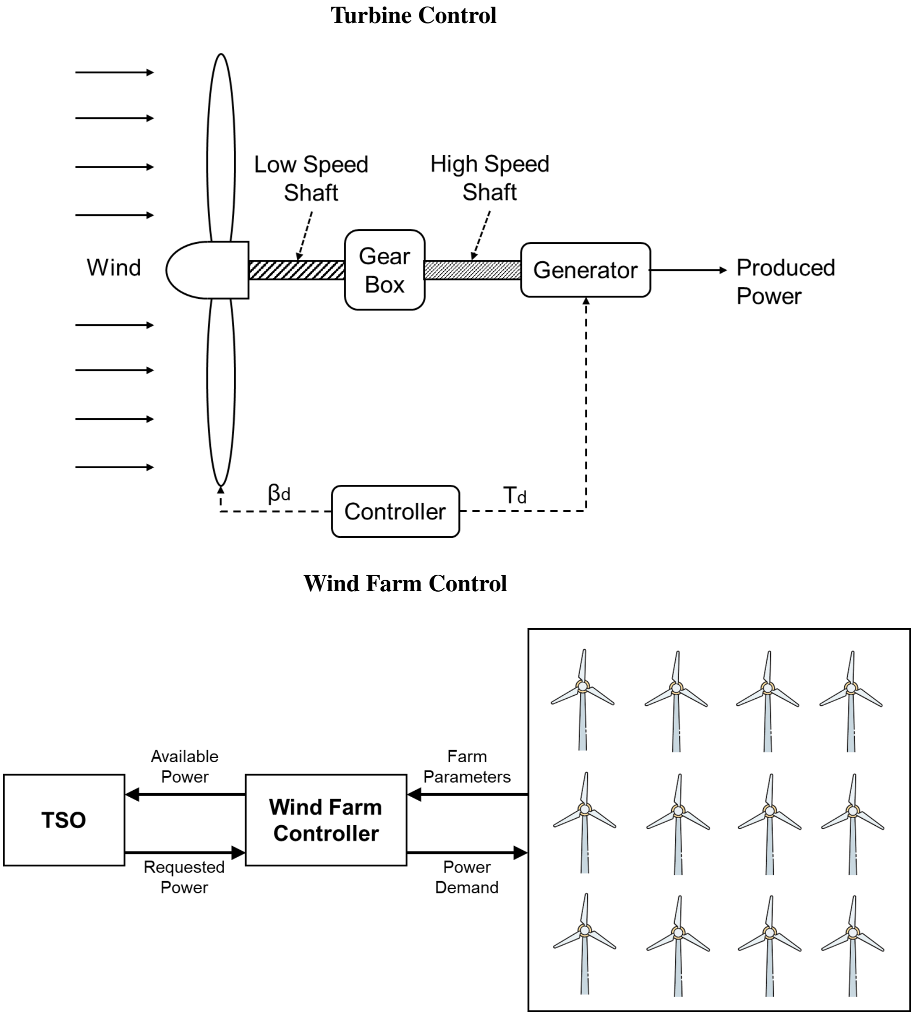
responsible for balancing the supply and demand of the UK's grid through the use of infrastructure owned by the transmission companies. The NESO grid code defines grid connected non-synchronous generators generically as "power park modules", which are categorised based on their location (on/offshore), whether they have an AC or DC substation, and the number of substations they are connected to, with no distinction between generation methods (NESO, 2025e; Fernández-Bustamante et al., 2021).

The current UK government have structured themselves around five core missions, which act as long term goals to drive the countries policy, one of these being "Make Britain a Clean Energy Superpower" also known as the Clean Energy Superpower Mission (CESM) (DESNZ, 2025). The CESM lays out how the UK can achieve their clean energy transition (DESNZ et al., 2025). The mission highlights priority challenges for both Clean Power 2030 and Net-Zero 2050, to achieve a clean and reliable future grid. Clean Power 2030 represents an important mid-term goal, whilst NESO's Future Energy Scenarios (FES) outline four key scenarios that demonstrate what the grid could look like in the long-term (NESO, 2025d). The FES 2025 documentation provides an in-depth description for each scenario which have been listed Table 4 in order of greatest to lowest amounts of renewable penetration.

The Holistic Transition scenario provides the greatest amount of clean energy. For the same reason, it also provides the least flexibility due to the lack of synchronous machines. In contrast, Hydrogen Evolution has the greatest amount of flexibility. The CESM highlights supply-side flexibility as a priority area, suggesting focus should be placed on low carbon fuels and storage solutions. This aligns with the pathways from FES 2025, with the predominant providers of flexibility being from storage, inter-connectors, and low carbon fuels. However, unlike the EU, the UK has neglected wind energy as a potential source of flexibility. Current research suggests that wind energy is capable of playing a critical role in supporting the grid and the net-zero transition through more flexible operation of wind turbines and by extension wind farms, via Wind Farm Control (Cole et al., 2023; Ackermann et al., 2024; Stock and Leithead, 2022; Dong et al., 2022).

4 Wind Farm Control

Wind Farm Control is a common term that covers a wide range of applications, as discussed in Knudsen et al. (2015) who also provide a general schematic for Wind Farm Control operation (Fig 2). A control layer is added above the turbine level, that provides a power reference to be targeted by each turbine based on turbine data, available power from the wind speed, and power demand from the network operator. In this section, first, the case for FWFC is presented in 4.1 as a sub-category of WFC. Before providing detail on power reference tracking in 4.2, given much of FWFC utilises some form of power reference tracking.


Turbine Control

Wind Farm Control

Figure 2. General wind turbine control and Wind Farm Control schematics with inputs and outputs

4.1 The Case for Flexible Wind Farm Control

At the turbine level, control tends to be split into two main areas; the first concerns problems such as protection of the electrical components as well as reactive power balance and battery storage for grid support (Dai et al., 2022; Chen et al., 2023; Song et al., 2025). The second includes adjustment of blade pitch, rotor shaft torque, and nacelle yaw, which are commonly used for power maximisation but could also be used to reduce power output, or to modify the wake and subsequent air flow through the wind farm.

Of the options beyond turbine-level power maximisation, the control of the air flow has received most attention and is commonly known as *Wind Farm Flow Control* (WFFC) (Andersson et al., 2021; Dong et al., 2022). In the majority of studies, the goal of WFFC has been power maximisation at the wind farm level through means such as wake steering or induction control. As highlighted by Eguinoa et al. (2021), WFFC can enable better grid integration and flexibility, through options such as power reference tracking and ancillary service provision. However, WFFC is a slow process, as the coupling between turbines is via the transport of air over long distances. For example, for two 100 m turbine rotors spaced 600 m apart in a wind speed of 10 m/s, the effect of WFFC would only be felt after approximately 1 minute, and therefore, would only be suitable for flexibility services with much longer time scales.

This paper uses the term *Flexible Wind Farm Control* (FWFC) to describe methods that provide flexibility as a core part of their operating strategy. FWFC can be considered a subcategory of Wind Farm Control distinct from WFFC. FWFC aims to control wind farm power output to facilitate better integration of wind energy into power systems as a primary goal. As a secondary goal, the impacts of the control approach on component degradation of turbines within the farm should be minimised. For example, idling a wind turbine reduces structural loads which have to be considered against increased loads associated with the start up and shut down of turbines. Ziegler et al. (2024) found that the overall load reductions of a turbine during full curtailment events (shutting down, idling, and restating all turbines) are only positive after an average of 63 minutes for onshore turbines and 200 for offshore. It was noted that this specific finding cannot be simply generalised. Their work only considers curtailment in the form of shutting down turbines and does not investigate the impact of complex curtailment strategies, which could see multiple shutdowns and startups in a period, or the use of partial curtailments.

To facilitate FWFC, new controllers allowing alternate modes of operation have been developed, for example recent releases of NREL's Reference Open Source Controller (ROSCO) (Abbas et al., 2024) and the Power Adjusting Controller (PAC) by Stock (2015), both enable the direct alteration of a turbines power output. While methods differ, a controller with the ability to adjust a turbine's power output can be coupled with a Wind Farm Controller to provide specific wind farm power outputs at the request of the TSO or the wind farm operators (Knudsen et al., 2015; Lim and Park, 2024).

4.2 Power Reference Tracking

The power output of a wind turbine is controlled at a turbine level, solely using the sensors of that turbine. To enable FWFC, a turbine's controller must be altered to allow the power to be adjusted. Hence, farm-level power demands can achieved through commands sent to each turbine. Recent releases of ROSCO, the open-source reference controller for wind turbines designed by NREL (now NLR), include power set-point control capabilities (Abbas et al., 2024). The ROSCO controller offers three methods for controlling a turbine's set-point through speed, torque, or pitch control. As mechanical power, P_m, and torque, T_m, are directly linked by the shaft speed, ω, by

$$P_m = T_m \omega, \tag{1}$$

it follows that any change in either generator torque or rotor speed would result in a proportional change in power. However, as the torque generated at a given wind speed depends on the rotor speed (as the power coefficient is a function of the tip speed ratio), torque and speed cannot be controlled independently, necessitating adjustment of the blade pitch to achieve a target mechanical power.

The torque control option included in ROSCO operates by changing the rated set-point value, thus restricting its applicability to above rated only. For below rated operation, through an increase to the minimum pitch angle. In the transition between below and above rated operation, some form of switching is necessary (NREL, 2025). Although the ROSCO documentation states that speed control is achieved through changing the rated value of the rotor speed only the pitch and demanded generator torque may be controlled, as seen in Fig 2. Describing the methodology simply as changing the rated speed contradicts this. As can be seen in Fig 3 when curtailing using the speed control option there is increased pitching above rated, whilst there is also increased torque below rated, when compared to the baseline. Additionally, the new switching point introduced below and above rated operation adds a layer of complexity to Wind Farm Controller design.

The turbine control approach approach proposed by Stock (2015), the PAC, avoids the addition of switching points and is generic, that is, it can be applied as an addition to any wind turbine controller. The PAC works across all operating regions of the turbine, as an interface between the turbine and a hierarchical Wind Farm Controller Stock and Leithead (2022). The Wind Farm Controller architecture follows the data flow shown in Fig 4. The key difference between the PAC-based approach and others is that changes in power for each turbine, ΔP_i, are set instead of turbine power set-points, P_i. The Farm Power Controller converts TSO requests into a requested change in wind farm power output, which is passed to the Distributed Controller. The Distributed Controller is designed to distribute the change in farm power amongst the turbines in the farm whilst accounting for one or more other metrics, such as impact on turbine loads. The distributed controller is informed of the status of each turbine via a system of 'flags', sent from the PAC in each wind turbine, which detail the current operational condition of the relevant turbine. The PAC was described in detail in Stock (2015) and its performance was assessed across a variety of conditions and test scenarios. The work published so far has focused on demonstrating the feasibility and flexibility of the proposed approach. Hur and Leithead (2016), Cole et al. (2020), and Routray and Hur (2024) have built on the theoretical framework of Stock (2015) to improve the robustness of Wind Farm Control approaches using the PAC.

To understand in detail how power set-point control for curtailment can impact overall wind farm performance it is critical to model the control implementation accurately. When comparing to the 'industry standard' method it is therefore critical to have a good understanding of how current wind farms are controlled. The control methods used are not openly available, making comparisons difficult and hence many of the reviewed studies do not directly compare to other methods (Hur and Leithead, 2016; Lim et al., 2022; Stock and Leithead, 2022). However, a presentation by Buller (2025) provides some insight into how

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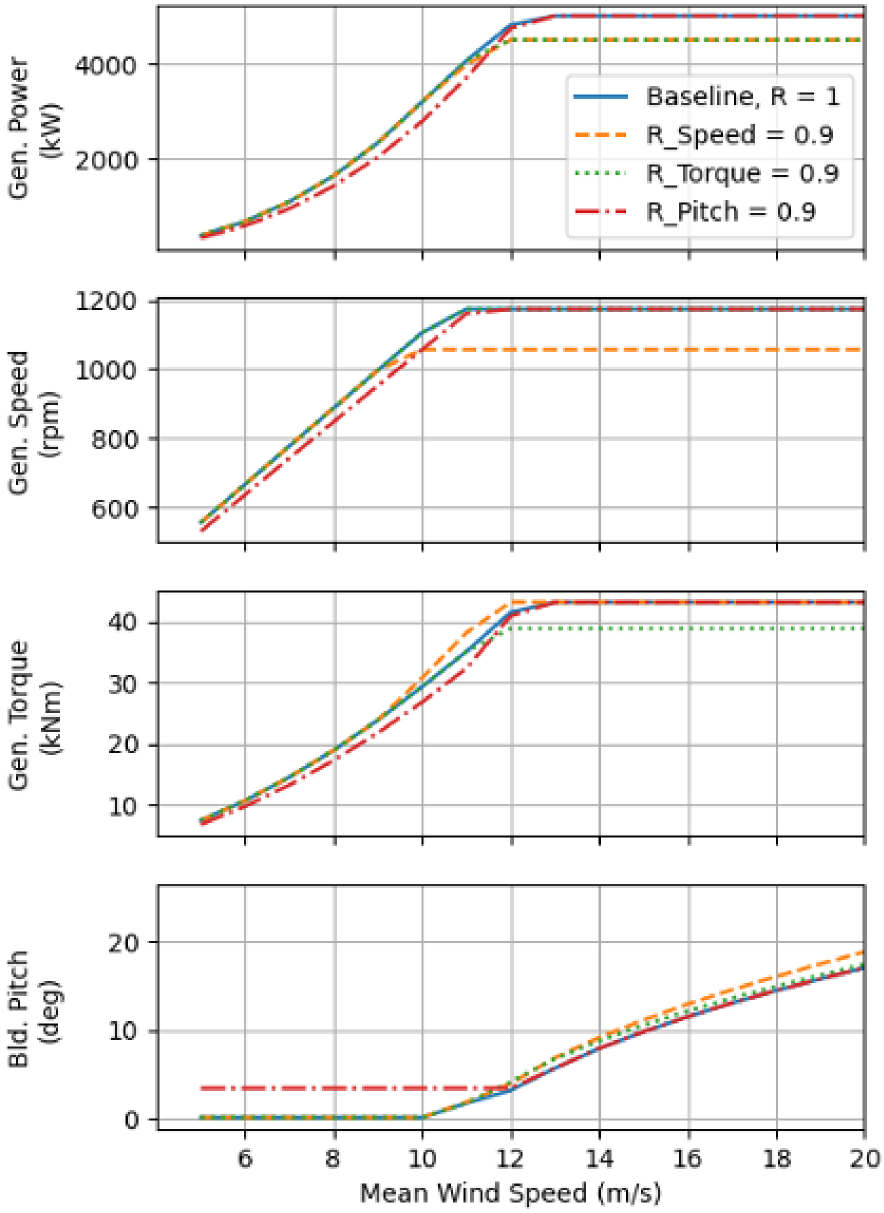

Figure 3. Comparison of the three power control methods for the NREL 5MW, when decreasing the available power to 90 % of its initial value (Abbas et al., 2024), licensed under the Apache License, Version 2.0

curtailment is conducted by industry. The SCADA data provided – which was normalised for data privacy – shows that the turbine controller curtails power by changing the rated power of the turbine, a similar method to that implemented in the ROSCO controller by Abbas et al. (2024). It is worth noting that the turbine rated power was altered in Buller (2025) seven

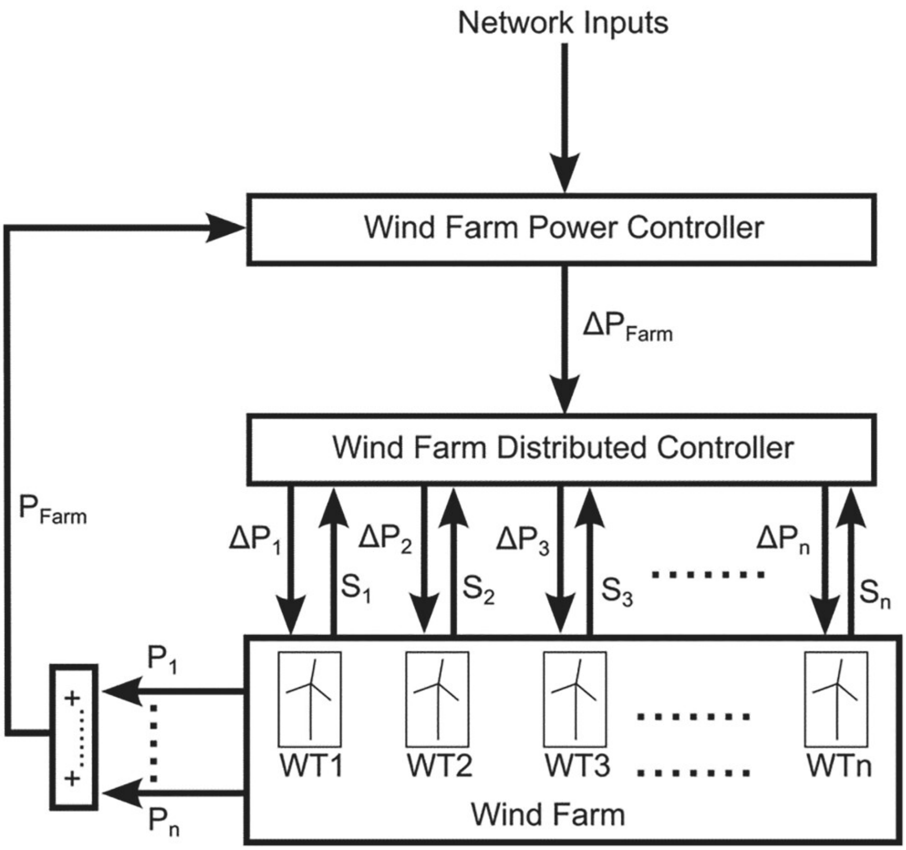

Figure 4. Wind Farm Control Architecture (Stock and Leithead, 2022), published under CC BY 4.0

times within an hour, likely due to some financial incentive or local constraint. Such frequent switching of the operational mode of the wind turbine was identified as being likely to have impacts on the overall loads, and hence lifetime, of the turbines.

5 Uses for Flexible Wind Farm Control

The issue of system flexibility in future renewable dominant power systems is becoming much more prevalent in discussions about future outlooks, with regulatory bodies highlighting the need for development in this critical area (DESNZ, 2025; Dedecca et al., 2025). The main strategies that provide flexibility are summarised in Table 5 and will be discussed further in this section. The need for improved system flexibility can be met by wind energy through a variety of different methods. An overview of the current capabilities of FWFC based on current literature is provided in sections 5.1 – 5.4. Sections 5.1 and 5.2 are outwith the primary scope of this report as they are primarily power electronics problems, but have been included for completeness due to the support that rotor side control (pitch and torque control) can provide. Each section is a distinct use case

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Table 5. Summary of Wind Farm Control strategies for enhancing grid stability.

Control Strategy	Description	References
Synthetic Inertia	Uses the kinetic energy of a turbine to mimic the response from synchronous generators	Fernández-Bustamante et al. (2021)
Fast Frequency Response (FFR)	Quick response to frequency deviation through active power control	Fernández-Bustamante et al. (2021); Cole et al. (2020)
Voltage and Reactive Power Control	Maintain voltage by adjusting reactive power	Ali et al. (2021)
Fault Ride Through (FRT)	Ability to maintain connected during a fault and stay within grid code requirements	Mali et al. (2014)
Co-located & Hybrid Systems	Integration of wind energy and other systems (i.e. Hydrogen, ESS, CCUS)	Shezan et al. (2023); Renewable UK (2025)

and demonstrates how FWFC can be used to integrate wind energy in a grid-friendly manner, in order to actively contribute to flexibility and reduce the negative impacts from increased wind penetration.

5.1 Voltage Control

Voltage control requires the management of reactive power which cannot be done through rotor side control at sub-cycle time scales. While rotor side control cannot be used to produce reactive power itself, nor respond at the necessary time scales, it can be used to support the production of reactive power. By managing the active power (mechanical power) output in a manner that provides the necessary for power electronics to adjust reactive power (Song et al., 2025). If the machine-end voltage of the turbine is kept constant, reductions in active power facilitate greater amounts of reactive power, while increasing the active power tightens the limit on reactive power, as shown in Fig 5. While Song et al. (2025) focussed on the reactive power control of DFIG based wind turbines, PMSG wind turbines also boast similar reactive power control capabilities (Dai et al., 2022; Yadav and Balasubramaniyan, 2025). As the Iberian blackout in the spring of 2025 was traced back by ENTSO-E (2026) to voltage support issues, amongst other factors, the possibility of wind farms providing additional headroom for voltage support through FWFC is a potential contributor towards grid stability.

5.2 Fault Ride Through

Similar to voltage control, Fault Ride Through involves reactive power provision among other requirements. There are some aspects of fault ride that rotor side control can support, primarily the decrease and restoration of active power. In the context of Low Voltage Ride Through (LVRT) and by extension Zero Voltage Ride Through (ZVRT) energy can be stored in the rotors of

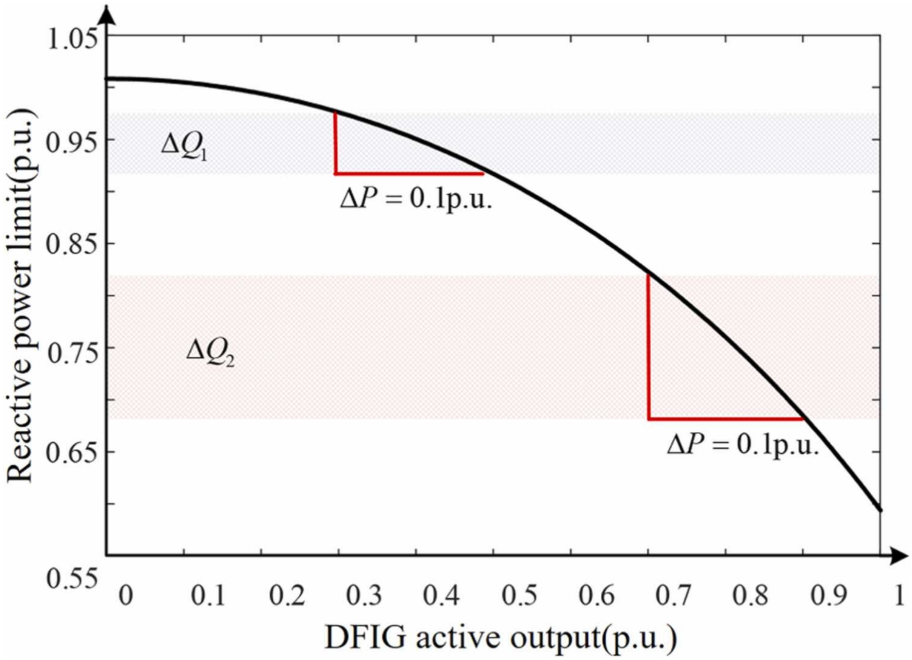

Figure 5. Reactive power limit curve (Song et al., 2025), published under Creative Commons CC-BY-NC-ND

the turbines as inertia which can be released later. Alternatively, turbines can be operated with strategies other than *maximum power point tracking* (MPPT), which would reduce their active power output. Doing so also has the benefit of reducing the size of batteries needed to store excess energy and an increased limit for reactive power (Mali et al., 2014). Following recovery of the fault, active power can be restored to required levels through power set-point control as discussed previously in section 4.2.

5.3 Frequency Control

Frequency control has received much more attention in the literature than other control strategies that focus on grid stability, largely due to the fact that the system frequency is a global measure of the system's state and therefore a key indicator of balancing requirements. Given the link between mechanical rotation, rotor inertia, system frequency, and system inertia, the relationship between mechanical power and frequency can be modelled using the swing equation for synchronous plant (Eq 2). The swing equation relates the angular velocity of the grid and the rotor, ω_g and ω_m respectively, the apparent power, S, and the total equivalent inertia, H, to the size of the power deviations between the mechanical shaft power, P_m, and the electrical active power, P_e (Fernández-Bustamante et al., 2021),

$$P_m(t) - P_e(t) = \frac{2S}{\omega_g} H \frac{d\omega_m}{dt} \tag{2}$$

Another important relationship to consider is the Rate of Change of Frequency (RoCoF), which is a good measure of the robustness of a grid. Immediately after a power imbalance, the rate of change from the nominal frequency (f_0) can be expressed as;

$$\text{RoCoF}\big|_{t=0^+} = \frac{\Delta P}{2Hf_0} \tag{3}$$

where ΔP is the difference between the supplied and demanded power.

When there is a power imbalance in a grid, the speed with which the system frequency changes is inversely proportion to the system inertia. Hence, as the inertia is reduced due to increased renewable penetration, the RoCoF from a given power imbalance becomes much more significant. Control systems can be used to replicate this effect, which is referred to here as synthetic inertia — which are also known as emulated inertia, virtual inertia, or hidden inertia. A synthetic inertia controller operates by increasing the power output of a wind turbine or farm proportional to the RoCoF, which limits the RoCoF and frequency nadir (Fernández-Bustamante et al., 2021; Stock, 2015). To further manage the RoCoF and frequency nadir, Zhang et al. (2022) propose an improved reserve scheduling approach that considers the uncertainties in power forecasting for reserve distribution and if the turbines are operational. Frequency support was provided through *Comprehensive Inertial Control* (CIC) which incorporates both synthetic inertial control and droop control, allowing wind turbines to mimic the behaviour active power-frequency droop and reactive power-voltage droop characteristics of synchronous generators (Hu et al., 2023). The authors considered the impacts of wake effects using the Jensen wake model, although the simulations are on a large timescale using constant hourly mean wind speeds, which do not capture the effects of turbulence. A further limitation is that the impact on turbine loads was not assessed.

Chen et al. (2023) developed a *Primary Frequency Control* (PFC) strategy based on a wind farm power reserve controller that minimises pitching action by over-speeding the turbine rotor, combined with a droop-controller. The proposed controller shows significant improvements in the ability of the turbines to store kinetic energy and minimises pitch usage compared to previous work by Chang-Chien et al. (2008). Whilst the method demonstrates the feasibility of the concept, the results are only for below rated wind speeds and use simple wind models which neglect turbulence and wake effects, which both have a major impact on turbine loads, which have not been quantified.

Studies of the contribution wind power plants to secondary response are limited, as highlighted by Loza et al. (2024) in their review on the grid-friendly integration of wind energy, which showed that primary response received the most attention in the literature, while secondary received the least. It was suggested that more work is needed towards developing hybrid frequency control strategies which combine the different time scales. Some work towards a hybrid frequency control system by Ullah et al. (2023) uses wind farm curtailment and a flexible load system to provide the secondary frequency response in an automatic generation control scheme. The contribution from wind power only comes in the case that supply is greater than demand, as it was deemed more economical to run turbines at maximum capacity instead of issuing a reserve capacity. This rationale may not necessarily hold in markets where operators are rewarded or reimbursed for their participation in the reserve markets or where the impacts of turbine loads on operation and maintenance are accounted for in the analysis.

Lim et al. (2022) demonstrated that overshooting a curtailment set-point produces a corresponding drop in frequency and proposed a method to select control strategies (synthetic inertia or curtailment) to reduce this dip. The selection method, summarised in Fig 6, identifies what wind farms should curtail and which should provide synthetic inertia. A clear reduction in

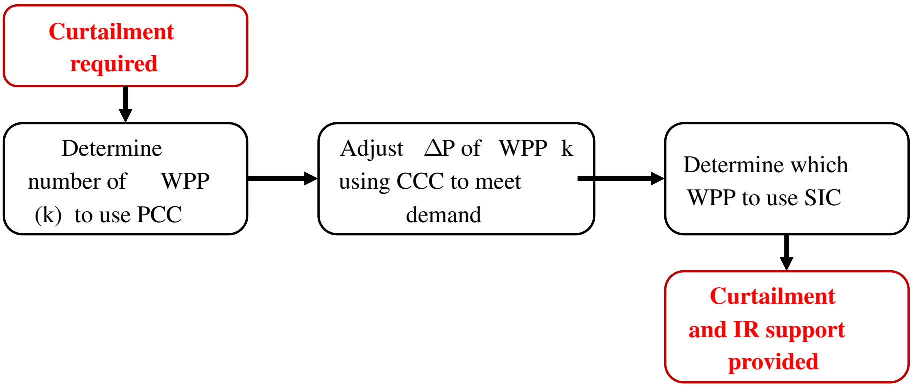

Figure 6. General methodology for the distribution of synthetic inertia control and curtailment control strategies, summarised from (Lim et al., 2022)

the magnitude of the frequency dip was shown. However, similar to other power-system-based approaches, the farm simulations are very high level with the authors assuming constant wind speeds, no wind farm dynamics, and no consideration of the reverse case, where wind farms are instructed to return to normal operation. Further work on a new approach by Lim and Park (2024), extended the simulations to include the end of the curtailment period, but did not address the other limitations.

5.4 Co-Location and Hybrid Systems

Wind farms can be co-located with other assets, such as demand sinks or generation sources, to maximise the value of shared resources such as grid connections and land access (Renewable UK, 2025). The co-location of wind can benefit grid flexibility, stability, and integration by resolving some of the issues related to the intermittent and uncertain nature of wind energy and demand (Stock et al., 2023; Renewable UK, 2025). The reduction of wind energy curtailment has seen significant attention recently, as curtailment volumes continue to increase due to the lack of infrastructure and demand, effectively wasting energy. One solution is to use curtailed energy for *Pumped Hydro Energy Storage* (PHES) or hydrogen production (Li et al., 2023; Storey et al., 2025).

Wind to hydrogen systems are capable of serving many purposes, as demonstrated by Li et al. (2025) who designed an integrated system with wind farms and *Hydrogen Production Units* (HPU) to provide frequency support and act as a hydrogen source for hydrogen-powered vessels. Their work demonstrated how a hybrid system such as this can participate in the ancillary markets but used simplified wind turbine and HPU models, neglecting the long term variability of wind or the impacts on degradation and *Levelized Cost of Hydrogen* (LCoH) of varying the active power of the HPU. Similar work by Stock et al. (2023), provides a proof of concept for the use of WFC to extend the battery life in a hybrid green hydrogen system. A power smoothing algorithm was used to reduce the number of cycles and depth of discharge needed from a battery to support the production of green hydrogen. Stock et al. (2023) showed that power smoothing through WFC could have a significant positive impact on the lifetime of batteries. Similarly to Li et al. (2025), electrolyser degradation was not included in the model, which would significantly overestimate the system's performance as discussed by Jafari et al. (2022), the same applies also to the dependence of round-trip efficiency on the power of electrolysers and *Energy Storage Systems* (ESS) (Virah-Sawmy et al., 2024). Additionally, the model developed by Stock et al. (2023) did not include a full implementation of the Wind Farm Control strategy, instead the assumption was made that the strategy would work as expected. The authors noted that future work should look to model the Wind Farm Control strategy as part of the simulation.

Transitioning to Net-Zero is likely to involve investments in CCUS technologies to reduce total emissions while still having the benefits of inherently flexible carbon emitting generation sources (DESNZ et al., 2025). Integrating CCUS with renewable generation can add a degree of flexibility by absorbing excess renewable energy instead of curtailing (Zantye et al., 2021). Although there is opportunity here, there are many technical barriers such as; the intermittent nature of renewable energy, the optimal control of carbon capture units, wind power utilisation, storage, and grid requirements. The technical barriers along with high associated costs and little financial incentive, especially given that carbon costs will decrease as the technology matures, make the implementation of CCUS a challenge (Flowers and Findlay, 2024). Radic Webster et al. investigated the optimal sizing of DAC units co-located on a 15 MW offshore wind turbine platform, focussing on independent control of the DAC units. Their work aimed to maximise the CO_2 capture rate and wind utilisation. However, assumptions were made that the power remains constant over a 20 minute period and neglects the effects of turbulence, which have a significant impact on the degradation of the batteries and likely the DAC units too. Similar work was carried out by Samani et al., which investigated how a CCU based chemical process can be integrated with wind energy. The co-located scheme uses a decision making process based on the day-ahead market, to forecast wind power production and optimise the day's chemical production through load shifting to maximise wind participation and profits. The two-stage process determines the base load of the chemical plant and FCR using day-ahead wind forecasts. The authors comment that more work is needed to integrate demand side response and ancillary service provision from renewables.

The recent AI boom has led to an increased demand worldwide for data centres, which will significantly increase the strain on power systems due to their large and variable electricity consumption, with the energy demand attributed to AI data centres expected to double by 2030 (IEA, 2026). Yang et al. (2022) showed that to offset the strain on the power system, it is possible to co-locate these demand sources with renewable energy, but the intermittent nature of renewables presents a problem for the equipment. Yang et al. (2022) also investigated the power smoothing of-so called green data centres, to reduce the negative impact from a fluctuating load, similar to the work with batteries performed by Stock et al. (2023). Through a combination of workload scheduling (load shifting) and use of batteries to smooth fluctuations, the authors maximise renewable energy participation. Though there is scope to incorporate Wind Farm Control to aid the battery in smoothing power fluctuations.

6 Future Outlook

The increase in the penetration of renewable energy has resulted in changes in the challenges faced within power systems. As demonstrated in this review, the primary challenge is shifting from ensuring adequate generation capacity towards managing the reduced flexibility associated with increased asynchronous renewable generation. Curtailment, while a problem in its own right, is a symptom of the wider flexibility issue due to increased renewable penetration. Future investment in improving grid infrastructure aims to address this, but will not completely eliminate the flexibility issue. Flexible Wind Farm Control not only has the clear benefit of improving flexibility, but also has much lower associated costs than system infrastructure upgrades.

Current policies and government targets acknowledge the need for increased flexibility, but it is clear that the potential for Flexible Wind Farm Control to play a role in this is not widely known. The EU highlights wind farms as being capable of supporting the transition through "system-friendly renewable energy generation", while the UK does not include wind energy in their flexibility needs. The literature shows that Flexible Wind Farm Control can technically support a power system's flexibility needs. Many of the reviewed studies adopt a power-systems perspective, relying on simplified turbine and farm models that neglect critical dynamics such as turbulence and wake effects.

With there being such a wide array of control techniques — particularly for frequency control — it is important to understand the mechanical load impacts on the turbine of the method compared to standard operation. Most of the studies reviewed do not done so. This comparison is especially important in cases like curtailment which can force turbines to operate in non-standard conditions. The same can also be said for the inclusion of degradation, as well as other dynamics associated with electrolysers, BESS, and related infrastructure.

There is significant opportunity for the co-location of wind with other electricity intensive infrastructure. In these scenarios, Flexible Wind Farm Control can be used in combination with control of demand sources to maximise renewable energy utilisation. Much of the work in this area considers infrastructure with a grid connection, but it is reasonable that this could also be extended to micro-grids or other weak grids. Work in this area must also still consider the impacts of mechanical loads.

7 Conclusions

This review has demonstrated the role Flexible Wind Farm Control can play in future power systems along with the gaps in the current literature. The reviewed literature demonstrates that wind farms are capable of supporting power systems through Flexible Wind Farm Control. There is a growing requirement for power system flexibility arising from the transition to Net-Zero, which can be provided through Flexible Wind Farm Control. Whilst research on Flexible Wind Farm Control shows promise, work is still in an early stage, requiring much more attention from both a policy, and technical standpoint in order to broaden our understanding of Flexible Wind Farm Control and its use cases. Alongside academic advances and policy changes, greater data availability and field tests would facilitate better understanding of the benefits of Flexible Wind Farm Control, as well as its impacts on wind turbines and the degradation of their components. In the short term, further work is needed to provide analysis of the load impacts of flexible control strategies, along with the creation of models that are both computationally efficient and incorporate essential dynamics such as turbulence and degradation.

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Competing interests. The authors declare that they have no conflict of interest.

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